STUDIES ON SPONTANEOUS HEATING LIABILITY OF SOME INDIAN COALS AND ITS PROTECTIVE MEASURES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF

MASTER OF TECHNOLOGY

IN

MINING ENGINEERING

BY

ALOK RANJAN MAHANANDA

DEPARTMENT OF MINING ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA-769008

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CERTIFICATE

This is to certify that the thesis entitled "**STUDIES ON SPONTANEOUS HEATING LIABILITY OF SOME INDIAN COALS AND ITS PROTECTIVE MEASURES**" submitted by **Sri Alok Ranjan Mahananda** in partial fulfilment of the requirements for the award of Master of Technology in Mining Engineering at the National Institute of Technology, Rourkela is an authentic work carried out by him under my guidance and supervision.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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Alok Ranjan Mahananda

Date :

CONTENTS

ABSTRACT

Spontaneous heating leading to fire in coal mines is a major problem worldwide and has been a great concern both for the industry and researchers in this field. Majority of fires existing today in Indian coalfields are mainly due to spontaneous combustion of coal. The auto oxidation of coal ultimately leads to spontaneous combustion which is the major root cause for the disastrous of coal mine. It is a slow process and the heat evolved is carried away by air. This process of self heating of coal or other carbonaceous material resulting eventually in its ignition is termed as 'spontaneous heating' or 'auto oxidation'. Coal can interact with oxygen in the air at ambient temperature liberating heat. If the heat is allowed to accumulate the interaction rate increases and may ultimately lead to fires known as spontaneous fires. The exact mechanism of the reaction of oxygen with coal is not completely understood as the chemical nature of coal is not yet fully established. So, determination of spontaneous heating liability of coal becomes an important criterion to predict the occurrence of spontaneous heating. Besides Protective measures to be employed may vary on numerous factors.

This project deals with the study of determination of spontaneous heating liability of coal and its variation with respect to the coal properties. It also states some protective measures that can be applied for coal storage during and after mining. Ten coal samples were collected from different collieries across India: Mahanadi coal fields (MCL), Bharat coking coalfield Limited (BCCL), Singreni Collieries Company Limited (SCCL), South Eastern Coalfields Limited (SECL), North Eastern Coalfields Limited (NECL), Western Coalfields Limited (WCL) and were subjected to different experimental techniques for assessment of their spontaneous heating liability.

LIST OF TABLE

LIST OF FIGURES

Chapter 1

INTRODUCTION

General

Objective

1. INTRODUCTION

1.1 GENERAL OVERVIEW

Coal Mine Fire is one of the major problems all over the world. A huge loss of around 300MT of coal every year is lost due to coal mine fire. Mine fires in coalfield are generally caused due to spontaneous combustion. Spontaneous combustion of coal means the process of self heating of coal in a self propellant manner resulting in ignition without any external supply of heat. Coal when exposed to air, it absorbs oxygen and evolves heat. This heat slowly dissipates into air. If the rate of oxidation is greater and the amount of heat dissipation is lower than the amount of heat accumulation then the coal reaches ignition temperature (Critical Temperature for Oxidation) and catches fire which is referred as spontaneous combustion.

Spontaneous Combustion results in serious accidents causing environment pollution, economic losses, loss in life, property etc. Spontaneous heating in any area of a mine affects working of other portions of the mine causing ventilation problems due to evolution of anoxic gases. Research Works and studies reveals that most of the mine fires resulting from spontaneous heating can be avoided if necessary arrangements are been carried out. Therefore there is a need of Protective measures for coal to prevent it from spontaneous combustion.

Protective measures for coal can only be applied if we are able to assess the susceptibility of coal towards spontaneous heating. Different types of coal have different susceptibility index and risk rating. This can provide us an idea how they are to be stored and what protective measures are to be taken. Storage of coal in stockpile and dumping of coal waste in spoil pile are to be so done that there is minimum chance of spontaneous heating.

A number of experiments are been carried out to determine the susceptibility index of coal numerous research work there is no single specific method that can be implemented for it occurrence. Hence the best method that increases the delay of spontaneous combustion is adopted. These methods differs a wide range depending on its applicability for the type of coal and factors responsible for spontaneous combustion. Therefore, it is needed to carry out a number of methods to conclude with fair accuracy.

1.2 OBJECTIVE OF THE PROJECT

1) Collection of coal samples from different coal fields across India.
2) Determination of Intrinsic Properties of coal samples and its Calorific values.
3) Assessment of susceptibility of coal to spontaneous combustion by various experimental techniques such as Crossing Point Temperature, Wet Oxidation Potential Difference method and Flammability Temperature,
4) Determination of various indexes of coal samples and its risk rating for spontaneous combustion.
5) To correlate various susceptibility indices with the intrinsic properties of coal.
6) To study the effect of different inhibitors on coal samples.
7) Preventive Measures that can be adopted to reduce Spontaneous combustion of coal.

Chapter 2

LITERATURE REVIEW

2 LITERATURE REVIEW

2.1. National Status

Indian coal mine have a long history of extensive fires and is probably as old as the history of mining itself. Coal mine fires can be traced back to the year 1865 when the first fire was reported in Raniganj Coalfield. Mine fires gained wide spread attention in India in 1930 with the occurrence of major fires in the Jharia Coal field (JCF). First fire occurred in 1916 in XII seam of Bhowrah colliery due to spontaneous heating in Jharia coalfield. In 1935, ten fires were reported. In 1937, the no. of fires reported in Jharia and Raniganj coalfield by the Coal Mining Committee was 28. In the year 1994, CMRI (Presently CIMFR), Dhanbad collected the data on fires reported to exist in different coalfields of India was about 196. In JCF along about 1864 million tonnes of coal is lying blocked in about 65 fires spread over an area of 17.32 square kilometres. This constitutes a staggering 12% of the total coal reserves. There is not only loss of lives of men in mines but also induce considerable economic losses to the organization involved by them. In Indian coal mine 75% of the coal fire appears due to spontaneous combustion.

2.2International Scenario

2.2.1 China

In China, the world‘s biggest coal producer with an annual output around 2.5 billion tons, coal fires are a dangerous problem. It has been calculated that some 10-20 million tons of coal uselessly burn annually, and that the same amount again is built inaccessible to mining. They are cantered in provinces of Xinjiang and Inner Mongolia and Ningxia, except exits from burned and inaccessible coal. These fires add to air pollution and substantially increased level of green house gas and have thereby become a problem which has gained International attention. China

underground coal fire are bedspread within a region debasing 5000 km east – west and 750 km north – south. It is accepted that fires in northern China consume a calculated amount of 100 – 200 MT of underground coal which is about 2 – 3% of world CO_2 production.

2.2.2. Germany

In Planitz, now a part of the city of Zwickau, a coal seam that had been burning since 1476 could only be allayed in 1860. In Dudweiler (Saarland) a coal seam fire caught fire around 1668 and is still burning today. Stinksteinwand (stinking stone wall) in Schwalbenthal on the eastern slope of the Hoher Meibner, where various seams ignites fire centuries ago and combustion gas continues to reach the surface today. Up to 10 coal fires per year in the Ruhr area of Germany are induced by spontaneous heating.

2.2.3. Indonesia

Coal and peat fires of Indonesia are often caught fires by forest fires near outcrop at the surface. No exact numbers of coal seam fires has been realized in Indonesia. The best data available come from a brief study based on systematic, on-the-ground notice. In 1998, a total 125 coal fires were placed and mapped within a 2-kilometer strip either side of a 100-kilometer extend of road north of Balikpapan to Samarinda in East Kalimantan, using hand-held Global Positioning System (GPS) equipment. Inferring the data to areas on Kalimantan and Sumatera underlain by known coal deposits, it was considered that more than 250,000 coal seam fires have been burning in Indonesia in 1998.

2.2.4. United States

Many coalfields in USA lead to spontaneous heating. The Federal Office of opencast Mining (OSM) asserts a database (AMLIS), which in 1999 named 150 fire zones. In Pennsylvania, 45

fires zones are known, the most famed being the fire in the Centralia mine in the hard coal region of Columbia County. In Colorado coal fires have been found as a consequence of variations in the groundwater level, which can increase the temperature of the coal up to 30 °C, enough to induce it to spontaneously ignite. Coal fires in Pennsylvania have been recorded since 1772, but the major fire occurred in 1869 when a ventilating furnace ignited wooden supports in the Avondale mine in Plymouth, suffocating 110 men trapped below ground. Since then, coal fires across Pennsylvania have destroyed floral and faunal habitats, consumed buildings, emitted toxic fumes into houses, contributed to different illness, induced land subsidence and many more. One of the underground mine fire in the US is the Centralia mine fire. The Centralia mine fire began when the Centralia Borough Council decided to burn trash to reduce volume of and control rodents in an abandoned strip-mining cut used as an unregulated dump at the edge of the town. Burning trash ignited anthracite in the Buck Mountain seam concealed behind the refuse and the fire spread along the seam to tunnels beneath Centralia.

A brief overview of different researchers on the various research works carried out by them in determining the liability of coal samples to spontaneous heating and protective measures adopted by them.

Feng et al (1973) – He termed CPT as relative ignition temperature. He methodised a composite Liability Index by using various results of CPT (Crossing Point Temperature) called as FCC Index.FCC Index was calculated as per the equation

$$\text{FCC Index} = \frac{\text{Average Heating Rate between } 110°\text{C and } 220°\text{C} * 100}{\text{Relative Ignition Temperature}}$$

The lower limit was set to 110°C (Heating rate) in order to ensure that all moisture had evaporated from the sample. The upper limit of 220°C was chosen in order to ensure there would have been a little evolution of Volatile matter below this temperature.

Mahajan, Tomita and Walker (1976) – They used DSC technique and reported DSC curves for 12different coal samples of various ranks in a helium atmosphere at a flow rate of 1ml/min and a temperature range of 100 to 580 °C at a constant heating rate of 10 °C/min. Samples of around 12 to 20 mg was used with reference material being alumina. They concluded that the thermal effects of coal, ranging in rank from Anthracite to Bituminous were endothermic in nature. In case of only Sub-Bituminous coal & Lignite exothermic heat was observed.

Gold (1980) – He demonstrated the occurrence of exothermic processes associated with the involvement of Volatile Matter in or near the plastic region of the samples. He concluded that the temperature and the magnitude of the exothermic peak were strongly affected by the particle size, heating rate and the sample mass.

Banerjee and Chakraborty (1967) - They suggested DTA (Differential Thermal Analysis) for the study of spontaneous combustion of coal, generally in classifying coal depending upon their susceptibility to self heating. They prescribed particular steps for DTA studies and recommended calcined Alumina as reference material for DTA experiments. Heating Rate was maintained at 5 °C/min. Typical temperatures obtained from various coals were included in this phenomenon to explain self heating process.

Mahadev and Ramlu (1985)- They proposed an Index known as MR Index and objected to the arbitrary selection of temperature range in the FCC Index.

$$\text{Liability Index} = \frac{\text{Heating Rate at CPT} * \text{Time taken to reach the Inflexion Point} * 10}{\text{Time taken to reach the CPT} * \text{Avg. Heating rate between the IP and CP}}$$

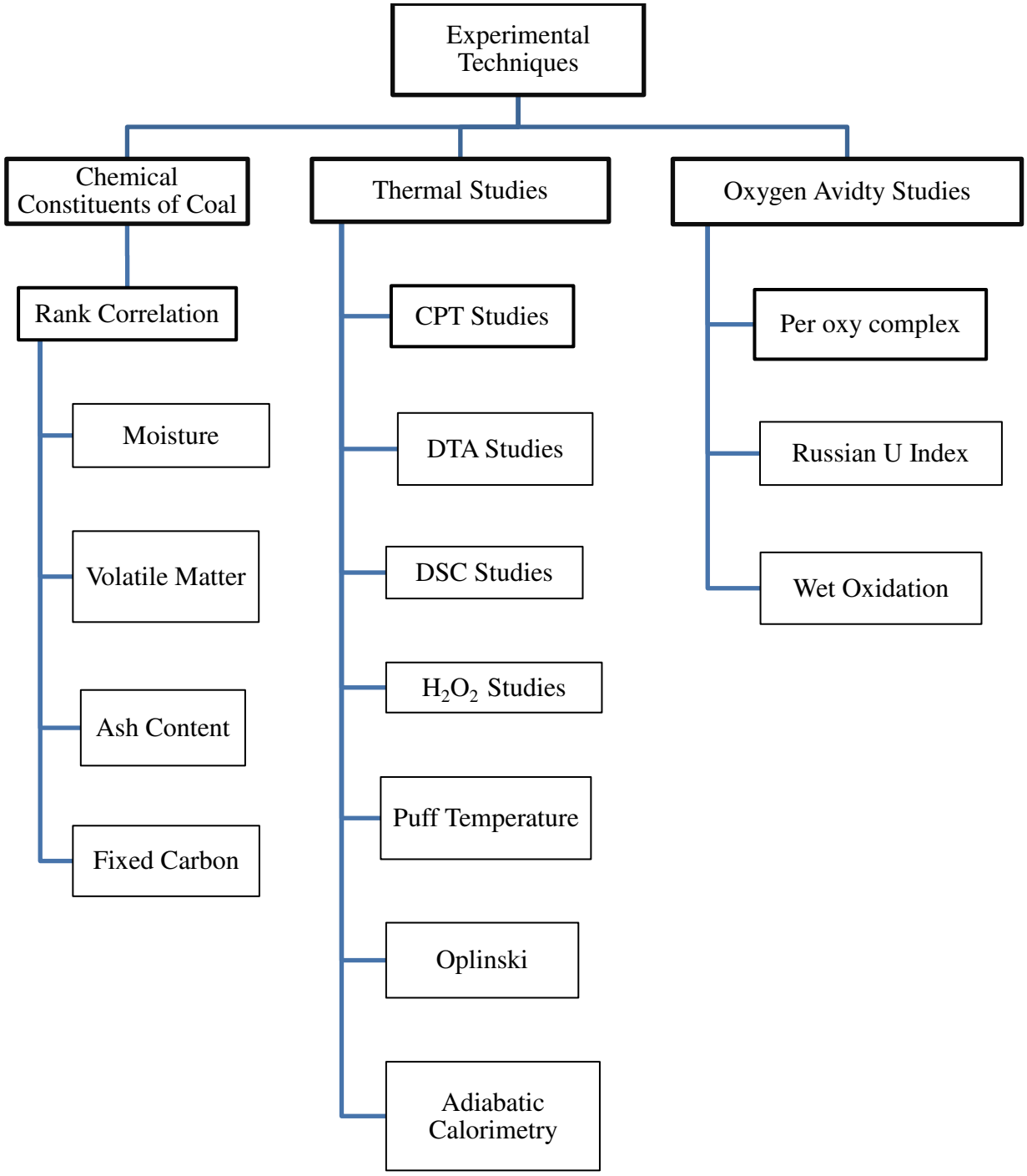
Where IP represents Inflexion Pont and CP represents Crossing Point. Reciprocal of the Liability Index was found to be increasing with Self Heating Liability.

Tarafdar & Guha (1989) - They reported the results of Wet Oxidation of coal with Alkaline Permanganate Solution involving measurement of differential temperature at different base temperature, at a constant heating rate. They experimented on 7 samples of known CPT by Wet Oxidation Method & then found out a correlation between CPT values & the corresponding differential peak temperatures, and between CPT & the observed Potential changes.They suggested that Potential Difference measurements during Wet oxidation of coal and the differential temperature may be used as alternative techniques for the assessment of liability towards spontaneous heating.

Bannerjee (1972) - He conducted CPT analysis of a number of Indian coal samples. He stated that coals with Crossing Point Temperatures between 120°C & 140°C can be categorised as highly susceptible to spontaneous heating. Coal samples with CPT from 140°C to 160°C can be categorised as moderately susceptible ones and those above 160°C are poorly susceptible.

Banerjee(1985)- observed various experimental techniques available worldwide to assess and analyse spontaneous heating susceptibility & summarised and organised them as follows:

2.1 Experimental Analysis of Spontaneous Heating Susceptibility.



Panigrahi et al. (1997) - They conducted experiments on 10 coal samples from Jharia. Carbon, Hydrogen, Nitrogen & Sulphur contents of these samples were determined by Fenton's method of Ultimate Analysis. CPT of above samples was also determined & attempts were made to correlate the Russian Index & CPT of coal samples with its basic constituents that were Carbon, Hydrogen and Ash Content and was categorised as a handy method of coal categorisation in Indian Context from the point of Susceptibility of Spontaneous Combustion.

Nandy et al.(1972)- correlated the variation in Crossing Point Temperature values with the Volatile Matter, Oxygen Percentage & the moisture content of coal. He observed that CPT was inversely proportional to the above components. But beyond 4 to 6% moisture content and 35%V.M there is not much change in CPT values. Generally above 4 to 6% moisture content in coal, CPT shows a rising trend.

Hence, it could be noticed from the above reviews that there is no universally accepted method for determining the spontaneous heating liability of various coal samples. Thus it was decided to carry out different experimental techniques to reach a clear conclusion viz. Wet Oxidation Potential Difference Analysis, Flammability Temperature Analysis, Crossing Point Temperature Analysis in order to accomplish the objectives of this present dissertation work.

Chapter 3

SPONTANEOUS HEATING OF COAL

Mechanism of Spontaneous Heating of coal.

Factors Affecting Spontaneous Heating Liability of coal.

Theories on Spontaneous Heating.

MECHANISM OF SPONTANEOUS HEATING OF COAL

3. Self-heating and spontaneous combustion

Self-ignition of materials means the onset of exothermic chemical reaction and subsequent temperature rise within the combustible material, without the action of an additional ignition source. Generally, self-ignition is supposed to occur when the thermal equilibrium between the two counter-acting effects of heat release due to the oxidation reaction and heat loss due to the heat transfer to the ambient is disturbed. When the rate of heat production exceeds the heat loss, a temperature rise within the material will consequently take place including a further acceleration of the reaction.

3.1 Natural oxidation of coal

In contact with the atmosphere nearly all types of coals show signs of weathering, which results in the decrease of the calorific value. A fact of great significance is that many coals are prone to spontaneous combustion. This hazard arises when the amount of heat evolved by oxidation exceeds the amount of heat dissipated by conduction, convection or radiation. The complete oxidation of carbon to carbon dioxide is an exothermic reaction that leads to heat emissions between 21 and 42 kJ per gram of coal, taking into account that coal is not composed of pure carbon. The chemical and heat balances involved in the low-temperature oxidation of coal, spontaneous combustion and final combustion are illustrated by a few fundamental process equations, demonstrating the exothermic nature of the reactions.

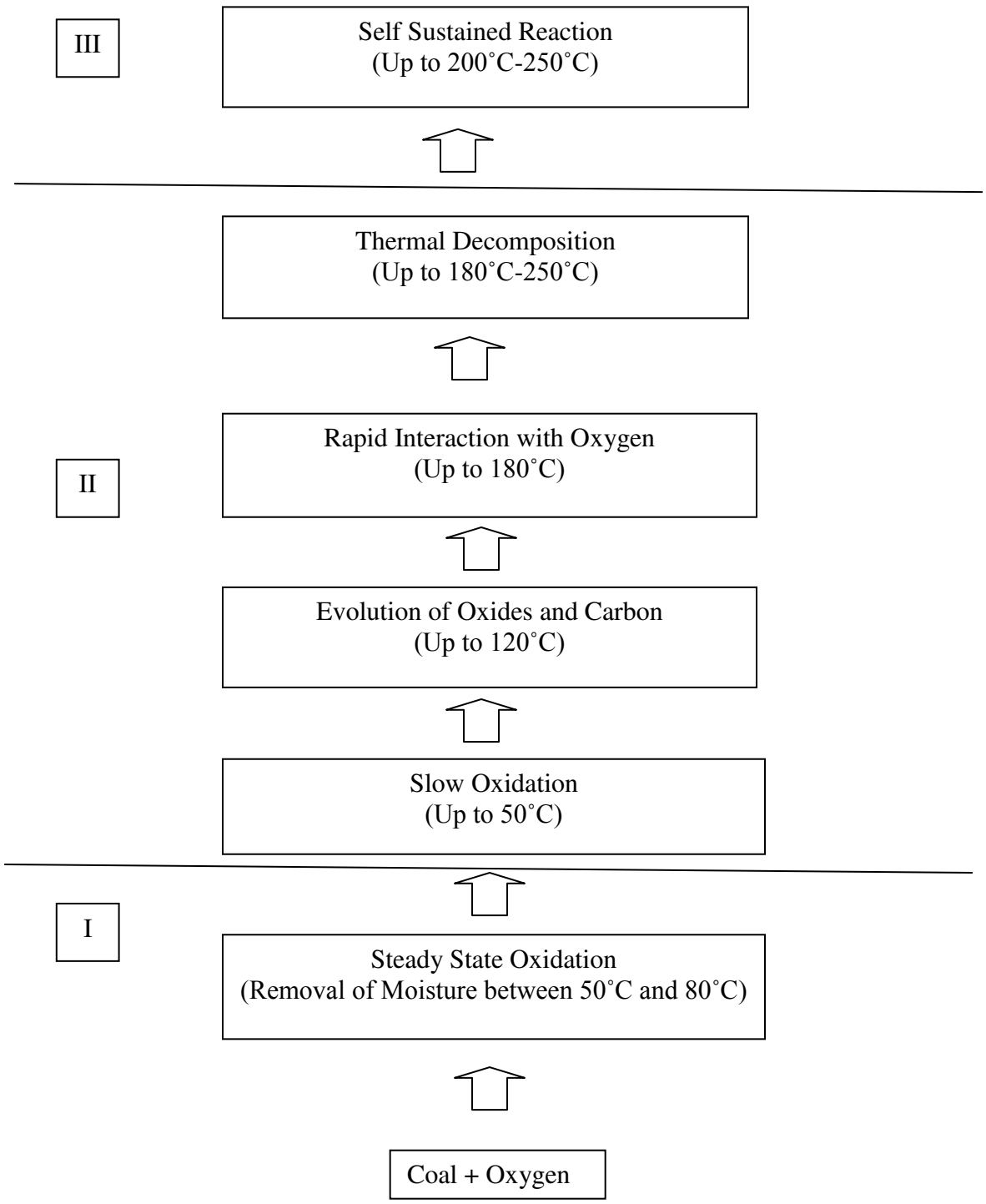


Figure 3.1: Sequential stages in the spontaneous combustion of coal

Coal is a stratified organic heterogeneous rock with carbon content varying from 95% in Anthracite to 60% in Lignite stage (young coal) with Bituminous and Sub Bituminous in

between. The automatic oxidation of coal is a complex physio- chemical process accompanied by the absorption of oxygen followed by formation of coal oxygen complex and further its decomposition to liberate heat. Because of the enormous diversity of composition of mineral matter in coal the complexity of the above process is tremendous. Various overlapping simultaneous reactions do take place during oxidation of the heterogeneous coal mass. Generally the proneness of coal to auto oxidation is proportional to the rate of oxidation of coal at ambient temperature. This low temperature aerial oxidation consists of various structural alteration of the coal mass resulting in the formation of numerous stable chain reactions due to large number of oxidation states of carbon followed by formation of a variety of strong carbon oxygen bonds. The observable, structural and compositional changes hint that the above process is a time dependent dynamic process. The entire process is heterogeneous.

$$C + O_2 \rightarrow CO_2 + 394 \text{ kJ/mol}$$

$$2C + O_2 \rightarrow 2CO + 170 \text{ kJ/mol}$$

$$2H_2 + O_2 \rightarrow H_2O + 241 \text{ kJ/mol}$$

Intrinsically- due to presence of two phases: solid and gas.

Extrinsically- due to diversified structural changes.

Generally coal gets heated up when it absorbs oxygen and the decomposition procedure can be explained as follows:

The rate of oxidation is petty sluggish below 50°C and it accelerates above 50°C but after it crosses 80°C a steady state is attained for a short interval of time probably due to removal of moisture. Following it removal of oxides of carbon begins at 120°C. The rate of interaction of oxygen with coal accelerates up to 180°C and next to decomposition starts between 120°C and

180°C. Finally the self sustained process of combustion begins somewhere around 220°C to 275°C with erotic rise in temperature until ignition point is reached.

3.2. Factors affecting spontaneous heating of coal

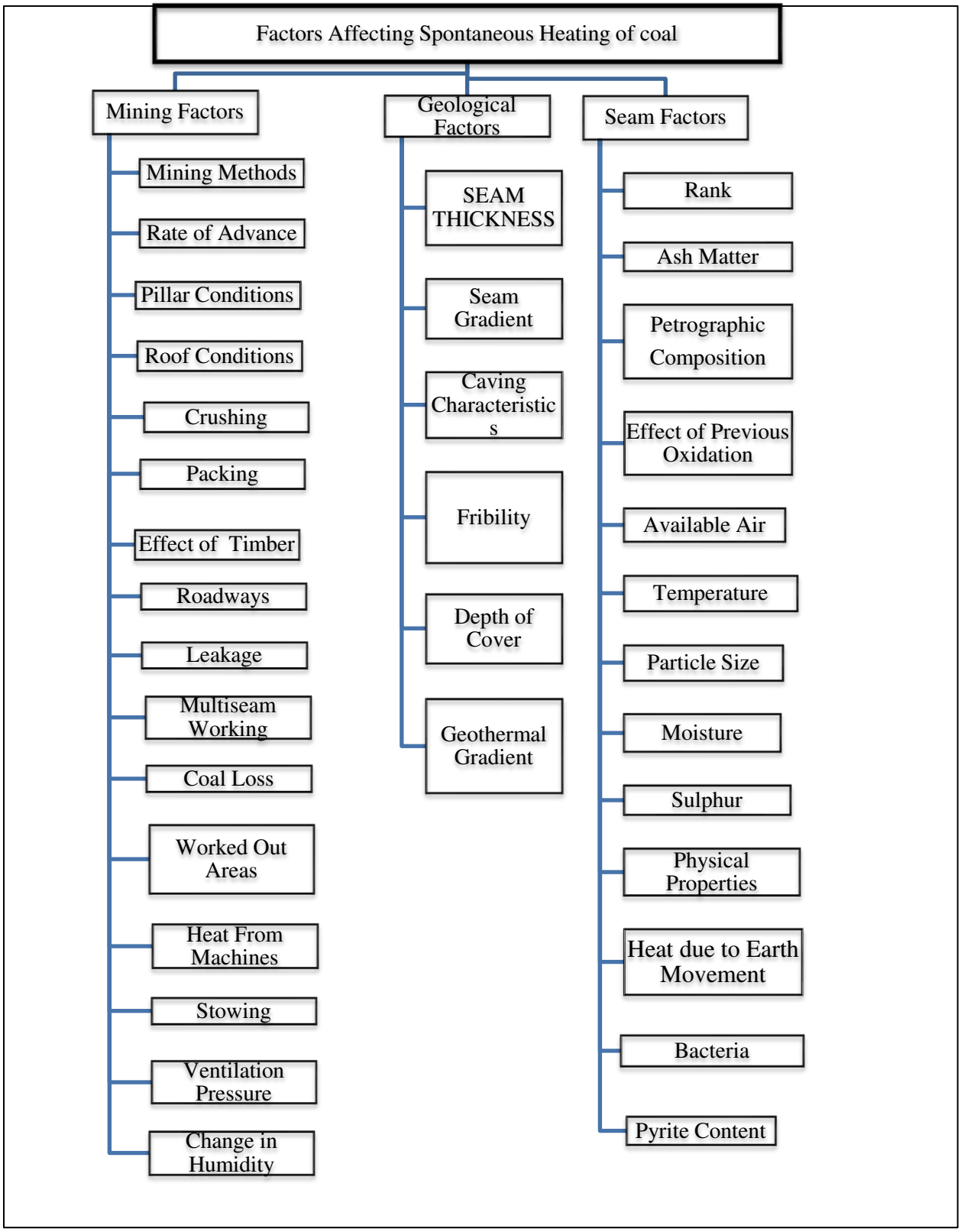
All coal seams have some propensity to spontaneously combust and it is important that a mine understands the risks associated with the coal it mines. The magnitude of the problem can be classified according to Intrinsic and Extrinsic factor.

Table No. 3.2.1 Factors Affecting Spontaneous Heating of Coal (Intrinsic and Extrinsic)

Intrinsic	Extrinsic
Coal composition	Climatic conditions(Temperature, Relative Humidity)
Rank and Petro graphic constituents	Stockpile compaction
Chemical Constituents	Coal Seams and Strata conditions
Coal friability	Method of working and ventilation
Particle size and surface area	Presence of timber or Roadways
Moisture content	Dump consolidation and other organic waste material
The presence of pyrites	Geological Disturbances

There are numerous methods which affect the Spontaneous heating of coal. The classifications of the factors as per categories are as follows.

Table No. 3.2.2 Classification of Factors affecting Spontaneous Heating of Coal



3.2.1. GEOLOGICAL FACTORS

Seam thickness: If the seam thickness is more than the part of the seam which can be mined in one go, such an area is more susceptible to spontaneous heating because the un-mined area will be exposed to a sluggish ventilation flow. It was found that spontaneous heating was invariably dependent on the method of working, friability of coal, type of ventilation and thickness of the seam. Generally the bands present with section of thick seam are more liable to spontaneous heating. The more thickly the seam, it becomes more difficult to avoid leaving high risk coal within the goaf region. Precisely, it is advisable to do selective mining in order to leave the lowest risk coal as waste. But such a thing is not always practically possible. On few occasions a coal floor or roof can be left un-mined where:

The natural roof or floor tends to be weak.

The seam is thick.

Presence of inferior coal below or above the mined area.

Seam gradient: Seams which are flat in gradient are less prone to spontaneous heating. But in case of steeper seams there arises convection currents due to difference in temperature leading to air currents in the goaf region. Also within the extracted areas there may be flow due to buoyancy due to difference in densities of methane, carbon dioxide, nitrogen at different elevation leading to flow of air influencing the development of spontaneous heating in waste, goaf or old workings.

Caving characteristics: In mines where partial extraction is done leaving sufficient pillars behind to support the super incumbent strata, the caving characteristics are of least significance.

But in such a situation it is desirable to fill the waste as fine material in order to reduce the amount of leakage air flow within the region of extraction. Thus the falling material occupies the maximum possible volume in order to fill the void created. It should be kept in mind the friable strata to fall should not be of carbonaceous type as it may lead to spontaneous heating and catching of fire of the left over pillars. Thus in such case the pillars should be extracted judiciously in order that the entire strata caves down.

Faulting: Spontaneous combustion is immensely influences by faulted ground. The grinding action along the fault plane with the fine coal formations may lead to spontaneous combustion. A fault generally slows down the pace of face advance leading to attendant risk of heat development.

Coal outbursts: It is majorly found in hard coal formation rather than soft and low grade coals. In coal outbursts generally fine coal is formed and is thrown away which might lead to passing of it through any place of active heating resulting in spontaneous combustion. Chances of coal outbursts are more with increasing depth. Factors associated with outbursts of spontaneous heating are:

1. Volcanic Activities

2. Mining Method

3. Geological Conditions

4. Characteristics of roof and floor

5. Characteristics of rock and coal

6. Contained Gas

7. Overburden stress

8. Permeability of the gas reservoir

Coal friability: Friable coals expose larger surface area resulting in higher rate of oxidation tending to achieve more heat per unit volume.

Depth of cover/Geothermal Gradient: With increase in depth, the natural strata temperature increases along with the in-situ base coal temperature. The geothermal gradient is 40 metre per degree centigrade. Thus high depth ensures high temperature of exposed strata after extraction which might lead to increased susceptibility to spontaneous combustion.

3.2.2. MINING FACTORS

Mining methods: Advancing long wall mining method leaves an extracted area lying between the entries to serve the working places. Generally the creation of ventilating pressure difference encourages air to pass though these areas leading to chances of spontaneous heating. Retreating system of extraction avoids above problem in cases where continuous stowing is done along with the advancement of the coal face, except the case when bleeder entry system is made to ventilate the waste.

Rate of advance: There is always entry of air to waste areas in close proximity to the working face by ventilating pressure or by bleed action. In such cases the rate of flow at times may be critical. So generally in a working face a piece of coal is exposed to air for the time period required in the advancing of the face. This time should not be excessive in order to avoid spontaneous heating.

Pillar size: It has a direct impact on liability of coal to spontaneous heating. Pillars should be of optimum size in order to avoid crushing at the edges leading to spontaneous heating. The depth of cover, strength of coal and other parameters determine the size of coal. Also crushing of pillars is another sign of methane emission and spontaneous heating.

Roof conditions: Poor roof generally allow shock waves to pass through it subsequently leading to have cracks within it. As a result the fallen areas of the roof are supported by timber supports. These cavities accumulate methane which acts as a source of ignition after localised spontaneous heating.

Crushing: It is primarily found at pillar edges and at worked out areas. As a result of crushing at pillar edges it may lead to leakage paths via itself tending to interaction of loose coal with air and may lead to auto oxidation. Also in worked out areas loose coal is present due to spalled pillars or roof falls and sluggish ventilation at such places may lead to spontaneous combustion.

Packing: Low quality packs often used in coal mines pose a big threat and are more liable to spontaneous combustion.

Effect of timber: In past generally timber props or other timber equipments were generally found in close proximity to spontaneous combustion regions, which gave rise to a school of thought that timber, is responsible for spontaneous heating.

Roadways : Roadways always pose a sign of threat and mostly leads to spontaneous combustion due to availability of loose coal as well as leakage air is available which adds up to auto oxidation of coal. More the amount of exposed coal more are the chances of liability of spontaneous heating.

The common points of such incidents are:

1. Junctions

2. Air Crossings

3. Doors, Regulators, Connecting Roads

4. Obstruction in Roads

5. Old Roadways

Leakage: For spontaneous heating to take place there must be a steady supply of oxygen and an area should be available where a build-up of heat is possible. Such a case is attained by air leaks through fissures available in solid coals resulting in shallow –seated heating circumstance. Above situation is found when leakage paths are available around air regulators, doors, air crossings etc or elsewhere high pressure gradient is available across the stoppings leading to drivage of air across it.

Multi seam workings: In case of multi seams where an unmined seam is available underneath another totally mined seam, it may lead to a situation where leakage of air may be from upper seam to lower seam leading to spontaneous heating chances of un-mined underlying coal seam.

Coal losses: Basically all mining methods lead to spillage of some remnant coal. It is never possible to extract 100% of coal by any mining method. So if there is availability of air and there is presence of some remaining crushed waste coal and there also exists a place where potential accumulation of heat is possible then it may pose a major threat resulting in spontaneous combustion.

Working out areas: Within the area of ventilating air-screen worked out areas pose a potential area for spontaneous combustion. Also addition of heat by working of machinery may demand additional air to be circulated requiring a high ventilating pressure with consequently increased risk of leakage.

Stowing: It is a method to control spontaneous combustion by sealing off the extracted area and reducing the gases in the goaf.

Ventilating pressure: In any mines the flow of air is generated by creating pressure difference. Such pressure differences are created by mine fans or by natural ventilation, but the distribution of pressure is primarily dependent on the distribution of the air quantity and resistance of the various mine paths. Wherever there is a pressure difference it leads rise to leakage or flow of air via strata or pillars etc. Thus ventilating pressure is one of the prime causes of spontaneous heating.

Barometric pressure: Generally air at any cost finds a way into a sealed –off area as a result of the underlying cases:

1. Barometric changes.

2. Continuous leakage resulting from a pressure difference between the intake and return stoppings.

3. Fluctuations in ventilating pressure resulting from the opening of doors and the movement of cages and mine cars.

Humidity : It is the property of coal to absorb moisture and when it does so from the ventilation air it gets heated up due to release of latent heat of condensation and due to chemisorptions

effects and the reverse happens when it losses moisture by evaporation. Thus humidity plays a major role in case of any misbalance.

3.2.3. SEAM FACTORS

Rank: The rank of coal is a function of the original plant debris from which it is formed and the amount of it has undergone. The increase in carbon content and decrease in oxygen content signifies high rank coal. Basically high rank coals oxidise very slowly in comparison with low rank coals. Low rank coal poses more prone to spontaneous heating.

Petrographic composition: Various petrographic tests do suggest that fusain is least reactive, and Durain is more reactive than Vitrain. Calculations of the reaction velocities of exinite, inertinite and vitrinite can help us in determining the spontaneous heating of coal. There are numerous methods which affect the Spontaneous heating of coal.

Temperature: With increase in temperature, the rate of absorption of oxygen increases substantially. With every 18 degree Fahrenheit rises in temperature the average rate of oxidation doubles.

Available air: In case of inadequate availability of oxygen, the rate of oxidation is very slow and there is no appreciable accumulation of heat. In case if the rate of air flow is high then the oxidation rate rises but at the same time the accumulated heat gets carried away by the flowing air. Thus if the flow rate is optimum the at that time it comprehensively supports spontaneous heating.

Particle size: Powdered coal poses more threat than solid coal. Solid coals have low permeability to allow passage of air through it. Thus small particles will show more proneness to spontaneous heating.

Moisture: Its effect is uncertain. Presence of moisture in small quantity adds up to spontaneous heating rate but large amount of moisture retards spontaneous heating rate. But in case of stockpiles drying and wetting continuously add up to rate of spontaneous heating.

Sulphur: Initially it was believed that pyrites add up to spontaneous heating due to the presence of sulphur but later research work justified that coal absorbs oxygen in the absence of sulphides also which changed the belief.

Ash/Mineral Matter: Chemicals play a major role in accelerating or retarding spontaneous heating. Alkalis act as accelerators where as borated and calcium chlorides act as retardants. Also preheating improves spontaneous heating liability of coal samples. High ash content retards spontaneous heating process while silica detoriates the rate.

Effect of extent of previous oxidation: Fresh coals are relatively more reactive to oxygen with respect to weathered coal which was justified from the fact that fresh coals had much lower ignition temperature than similar weathered coal.

Physical properties: Physical properties as porosity, thermal conductivity, hardness, specific heat can also do affect the rate of oxidation.

Heating due to earth movement: Heat evolved during crushing of rocks, goaf fall or pillar crushing may act as a cause of starting of self heating process.

Bacteria: Bacteria's such as thio bacillus ferro-oxidants and ferro-bacillus thio-oxidants can play a major role during the auto oxidation process of coal. These bacteria's are inactive at -193°C and 560 °C.

Pyrite contents: The sulphides present in coal are pyrite, marcasite, sparelite, galena, chalcopyrite and melnikovite-pyrite. Pyrites generally show catalytic effect as their oxidised product accelerates the rate of oxidation of organic compounds present in coal. The pyrite oxidation leads to formation of ferric ions which catalyzes the reaction. Also pyrite oxidation results in swelling which in turn causes breakage of the coal particles increasing the surface area for enhanced oxidation.

Thermal conductivity: In solid coals heat transfer is by conduction where as in broken coal heat transfer is by conduction and convection and it predominates at higher compactions. Convection gets enhanced at high temperature and low compactions, when moisture is evaporated and condensed. Moist coals with moisture around 5-7% are highly conductive.

3.3. THEORIES OF SPONTANEOUS COMBUSTION OF COAL

3.3.1 Pyrite Theory-There has been quite a few cases of heating due to oxidation of pyrites in pyrite mines. Heating can be availed in coal by presence of pyrite in considerable amount in finely powdered and dispersed state being comprehended by moisture. The reaction of pyrites with oxygen in presence of moisture is exothermic and yields product of greater volume which leads to increase in surface area of the coal thus ensuring increased rate of oxidation.

$$2\ Fe\ S_2 + 7 0_2 + 16 H_2O = 2\ H_2SO_4 + 2\ Fe\ S0_4.7\ H_2O + 316\ kcal$$

The oxidation of pyrite during weathering of coal seam may be represented by

$$Fe\ S_2 + 15/4\ O_2 + 9/2\ H_2O = Fe\ O.OH + 2\ H_2SO_4$$

Above equations suggest that oxygen and moisture are two prime weathering agents, which contribute to the pyrite alteration shown and it also leads to formation of sulphuric acid as by product of the alteration process. Presence of moisture doubles the reactivity rate of coal and presence of pyrite in dispersed form 10 folds the actual reaction rate.

Presence of pyrite in less of 5% showed negligible effect.

3.3.2.Bacterial Theory-Earlier bacteria was considered to add up to self- ignition of coal but further investigations clarified that bacteria's hardly had any influence on self heating of coal. The contribution of bacteria towards heating cannot be totally ruled out due to observance of spontaneous heating in haystacks due to bacterial action. Still, there is no justified fact to obey or discard the above concept.

3.3.3. Phenol Theory-Experimental research and investigations have justified that poly phenols and phenolic hydroxyls oxidize faster than many other organic groups. This theory is convincing as well as interesting as it drives a way in determining liability of coal to spontaneous heating.

3.3.4 Humidity theory-It stated that the quantity of heat required in removing water from coal is much high than the quantity of heat liberated by atmospheric oxidation of coal. The temperature of heating would definitely decrease if the evaporation is to be done at the cost of heating. But as a matter of fact water is one of the oxidation product formed during low temperature oxidation of coal along with CO and CO_2.

3.3.6 Coal-Oxygen Complex Theory-The native radical sight is the point of initiation of oxidation of coal. The formation of peroxyl radical and hydro peroxides justifies the fact that during the formation mechanism oxygen and moisture are initially incorporated into an organic

matrix. In fact these species may react, decompose, reform, alter to form a wide range of complex showing oxygen functionality in matrix or gaseous product form.

Kroger and Beier claimed that coal oxygen interaction occurs via formation of peroxy complex. The peroxy radical along with water lead to the formation of OH and OOH radicals. The above process consists of 3 stages:

1. The physical adsorption of oxygen which takes place at low temperatures and it requires low activation energy.

2. The Chemisorptions step where motion of complex containing active form of oxygen called per oxygen occurred and it occurred between temperature ranges 70°C to 80°C.Much amount of heat is involved in this process.

3. Rapid chemical reaction resulting in decomposition of per-oxygen formed leading to release of CO, CO_2 and H_2O and finally active combustion taking place.

3.4 Effects of Spontaneous Heating

Spontaneous heating has adverse effect on environment, wildlife and economy of the country. The adverse effect can be classified into following categories.

1) Water Management
    a) Poor Quality Mine Water
    b) Acid Mine Drainage
    c) Mine Tailings
2) Land Use Management

a) Land and surroundings

b) Waste Management

c) River Water Pollution

d) Wildlife

e) Subsidence

3) Air Pollution

a) Air Emissions

b) Mercury Emission

c) Annual Excess Deaths

d) Economic Costs

4) Green House Gas Emission and Global Warming

5) Radiation Exposure

6) Nation and Economy

7) Ecosystem and Habitat

Fig. No. 3.4.1 Effect of coal fire due to Spontaneous Heating

(http://www.itc.nl/~coalfire/photos/overview.html , www.sapient-horizons.com and www.uk.comsol.com)

Fire in Coal Stock pile

Fumes and noxious gas emission

Surface Fire

Exhalation crack due to coal fire

Subsidence due to coal fire.

Underground Coal fire

Chapter 4

EXPERIMENTAL INVESTIGATION

Sample Collection and Preparation

Proximate Analysis

Determination of Calorific Value

Crossing Point Temperature

Flammability Temperature

Wet Oxidation Potential Analysis

EXPERIMENTAL INVESTIGATION

Sample Collection and Preparation

For carrying out the experimental study, samples were collected from different collieries across India by channel sampling and bulk sampling method. The intrinsic properties of the collected samples were determined by proximate analysis. Determination of calorific value was done by Bomb Calorimeter. Various Liability Index and susceptibility indices were determined by Crossing Point Temperature, Flammability Temperature and Wet Oxidation Potential analysis Experiments. Correlation coefficients were determined for dependence of susceptibility indices over intrinsic properties of coal.

4.1Sampling (IS 436 Part 1/Section 1-1964 and IS 436 Part II-1965)

Coal is a highly heterogeneous substance in terms of the inorganic and organic constituents and exhibits wide variability with respect to size and chemical composition of the particles. An estimation of the true value of the desired parameters of a bulk material, through analysis on a few grams of test sample is problem. The basic purpose of collecting and preparing a sample of coal is to provide a test sample which when analysed will provide the test results representative of the lot sampled. In order that the sample represents the coal from which it is taken, it is collected by taking a definite number of increments distributed throughout the whole volume of coal. Sampling is the process by which inference is made to the whole by examining a part. The purpose of sampling is to provide various types of statistical information of a qualitative or quantitative nature about the whole by examining a few selected units. The sampling method is the scientific procedure of selecting the sampling units would provide the required estimates with associated margins of uncertainty, arising from examining only a part and not the whole.

a. Channel sampling

b. Chip sampling

c. Grab sampling

d. Bulk sampling

e. Drill hole sampling

For collection of sample for this project Channel Sampling and Bulk Sampling was done at various mines. The seams were chosen of various collieries and a section of 10 cm width and 10 cm depth was marked and was drilled or picked out.

4.1.1Steps of channel sampling

Channel Sampling is carried out in a series of steps:

1. Preparation of the surface: The surface is cleaned thoroughly by using scrubbers or brushes in order to remove dirt, dust, oxidised part of coal being exposed and other soluble salts. Also at times the upper layer is chipped up to 10 cm thickness in order to expose a fresh face to continue with.

2. Demarcation of the channel: After cleaning the surface, a channel was demarked by drawing two parallel lines 12-15 cm apart by the use of chalk or paint.

3. Cutting the channel: Following it the channel was cut by the use of a hand pick (prospectors pick). Although in case of cutting channel in soft coal mines hand picks are used but in case of hard coal generally a light weight air operated drill machine is used. In case of underground mines drill machines are used to cut channels in case where more no of samples are to be collected in a single shift.

4. Collection the sample: A sheet of canvas was spread on the floor in order to collect the coal chips as they fall through.

5. Labelling the sample: After collecting the coal sample the canvas bag was wrapped through and was tagged .Then the tagged sac was brought out of the mine.

Bulk Method is the simplest method of collecting samples. Bulk Sampling refers to the removing of large mineralized rock typically over fifty tonnes, selected to be representative of the potential ore body, in order to do mineral processing tests. It is done where schematic sampling methods do not give a representative scale. Large scale sampling or bulk sampling eradicates the effect of irregular distribution of value or minor. A small portion of the sample was considered for the experimental analysis.

The collected samples from different coalfields were brought to the laboratory. It was then crushed to smaller pieces. Coning and quartering procedure was done in order to get a small representative sample of the entire coal seam. Finally the samples were grounded and screened (sieving) to different size of - 212 (micron), -100 to 200, -100 etc according to the desired requirement of the experiment. Then the samples were stored in sealed packets for further analysis process. It was placed in moisture oven to make it air dry.

The major collieries are located in the northeast and southwest zone of India. The map below shows the location of different reserves present in India.

Figure No. 4.1.1 Map showing the distribution of Coal fields in India

Figure No. 4.1.1 Collection of Sample from different Coal fields in India

Samples are collected in these regions to provide a thorough idea on spontaneous combustion. Ten samples were collected by the following procedure from different colliery belonging to NECL, MCL, BCCL, SECL, SCCL and WCL.

4.2. PROXIMATE ANALYSIS

Chemical composition of the coal is defined in terms of its proximate and ultimate (elemental) analyses. The parameters of proximate analysis are moisture, volatile matter, ash, and fixed carbon. For determination of Proximate Analysis the method specified by IS(Indian Standard) 1350(Part-1)-1969 was followed.

4.2.1 Determination of Moisture Content

Coal, due to its nature, origin and occurrence, is always associated with some amount of moisture, which is both physically and chemically bound. It is differentiated between external and inherent moisture. When a wet coal is exposed to atmosphere, the external moisture evaporates, but the apparently dry coal still contains some moisture, which can be removed only on heating above 100°C. External moisture is also called accidental or free moisture, where as inherent moisture is termed as equilibrium or air-dried or hygroscopic moisture. The quantity of external moisture depends mainly on the mode of occurrence and handling of coal, but the air-dried moisture is related to the inherent hygroscopic nature of the coal.

Experimental Procedure -1g of finely powdered air-dried coal sample (-212μ) was weighed in a silica crucible and was placed inside an electric hot air oven (Fig no 4.2.1) maintained at 108°C. The crucible with the coal sample was kept in the oven for 1.5 hours and was then taken out with a pair of tongues, cooled in desiccators for about 15 minutes and then weighed. The loss in weight was reported as moisture (on percentage basis). The calculation was done as per the following.

$$\% \textbf{ Moisture} = \frac{\mathbf{Y - Z}}{\mathbf{Y - X}}$$

Where X = weight of empty crucible, gm

Y = weight of crucible + coal sample before heating, gm

Z = weight of crucible + coal sample after heating, gm

Y - X = weight of coal sample, gm

Y- Z = weight of moisture, gm

Figure No.4.2.1 Muffle Furnace for Ash Content & Volatile Matter Determination and Oven for Moisture Content Determination. (www.genlab.co.uk)

4.2.2 Determination of Volatile Matter Content

The loss of mass, corrected for moisture, which results when coal is heated in specified equipment under prescribed conditions, is referred to as volatile matter. The matter lost is composed of materials that form upon the thermal decomposition of the various components of coal. Some of the constituents of coal volatile matter are hydrogen, carbon monoxide, methane, other hydrocarbons, tar vapours, ammonia, some organic sulphur, oxygen containing compounds and some incombustible gases, such as carbon dioxide and water vapour.

Experimental Procedure

For the determination of volatile matter a special volatile matter silica crucible (38mm height, 25mm external diameter and 22mm internal diameter) was used. The empty volatile matter crucible was weighed. Approximately 1g of coal sample (-212 size) was weighed in the volatile matter crucible and it was placed inside a muffle furnace maintained at 925°C with the lid covering the crucible. The heating was carried I the muffle furnace (Fig no. 4.2.2) out exactly for seven minutes, after which the crucible was removed, cooled in air, then in a desiccators and weighed again. The calculation was done as per the following.

$$\% \textbf{ Volatile Matter} = \frac{\mathbf{Y - Z}}{\mathbf{Y - X}} * \mathbf{100 - M}$$

Where X = weight of empty crucible, g

Y = weight of crucible + coal sample before heating, g

Z = weight of crucible + coal sample after heating, g

Y -X = weight of coal sample, g

Y- Z = weight of volatile matter + moisture, g

4.2.3 Determination of Ash Content

Coal ash is the residue remaining after the combustion of coal under specified conditions. It does not occur as such in the coal, but is formed as the result of chemical changes that take place in the mineral matter during the combustion process. Ash and mineral matter of coal are therefore not identical.

There are two types of ash forming materials in coal: extraneous and inherent mineral matters. The extraneous mineral matter consists of materials such as calcium, magnesium and ferrous carbonates, pyrite, marcasite, clays, shales, sand and gypsum. The extraneous mineral matter owes its origin to the substances which get associated with the decaying vegetable material during its conversion to coal, which is difficult to remove by mechanical methods. Rocks and dirt getting mixed up during mining and handling of coal. Inherent mineral matter represents the inorganic elements combined with organic components of coal. The origin of such materials is probably the plant materials from which the coal was formed.

Ash from inherent mineral matter is insignificant as far as the total quantity of ash is concerned. But Indian coals suffer from the major disadvantage, that the mineral matter content is not only high, but of intimately associated type, due to its drift origin.

Experimental Procedure

The empty crucible was cleaned by heating in a muffle furnace for one hour at 800°C so that other mineral matter if presents get burnt. It was taken out, cooled to room temperature and the weight is taken. Approximately 1gm of coal sample was weighed in the crucible and placed in a muffle furnace at 450°C for 30 minutes and the temperature of the furnace was raised to 850°C for 1hour. The crucible was taken out and placed in desiccators and weighed.

$$\% \textbf{ Ash} = \frac{\mathbf{Z - X}}{\mathbf{Y - X}}$$

Where X = weight of empty crucible in grams

Y = weight of coal sample + crucible in grams (Before heating)

Z = weight of coal sample + crucible in grams (After heating)

Y - X = weight of coal sample, gm

Z - X = weight of ash, gm

4.2.4 Determination of Fixed Carbon (FC)

Fixed carbon (FC) is by definition, the mathematical remaining after the determination of moisture, volatile matter and ash.

FC= 100-(VM+M+A)

It is, in fact a measure of the solid combustible material in coal after the expulsion of volatile matter. Fixed carbon plus ash represent the approximate yield of coke from coal. The fixed carbon value is determined by subtracting from 100 the resultant summation of moisture, volatile matter and ash, with all percentage on the same moisture reference base.

The moisture (M), volatile matter (VM), Ash and Fixed carbon content of coal determined by following the above procedure is presented in Table 4.1.

Table no 4.2.4 Volatile Matter (VM), Ash (A), Moisture (M) and Fixed Carbon (FC) of coal

Sl. No.	Sample	Moisture	Ash Matter	Volatile Matter	Fixed Carbon
1	MCL1	13.575	32.015	11.3	43.11
2	NEC	3.41	39.2	2.005	55.385
3	SECL1	10.215	29.115	26.01	34.66
4	WCL	12.32	31.56	11.915	44.205
5	SCCL	6.95	27.795	25.535	39.72
6	BCCL	1.3	17.23	26.845	54.625
7	SECL2	6.75	29.905	23.46	39.885
8	MCL2	6.955	24.94	33.83	34.275
9	MCL3	8.236	28.975	29.51	43.28
10	MCL4	6.125	23.31	28.59	41.075

4.3. Determination of Calorific Value

Calorific Value

The energy value of coal, or the fuel content, is the amount of potential energy in coal that can be converted into actual heating ability. The process of measuring the heat of chemical reactions or physical changes as well as heat capacity is called calorimetry and the object used for measuring the energy value is called as calorimeter. The value differs with grades of coal or materials as different materials of different grades produces differing amounts of heat for a given mass.

A bomb calorimeter consists of a small cup to contain the sample, oxygen, a stainless steel bomb, water, a stirrer, a thermometer, the insulating container (to prevent heat flow from the calorimeter to the surroundings) and ignition circuit connected to the bomb. By using stainless steel for the bomb, the reaction will occur with no volume change observed. `It is a type of constant-volume calorimeter used in measuring the heat of combustion of a particular reaction. They withstand a large pressure within the

Fig. No. 4.3.1Bomb Calorimeter
(www.parrinst.com)

calorimeter as the reaction is being measured. Electrical energy is used to ignite the fuel; as the fuel is burning, it will heat up the surrounding air, which expands and escapes through a tube that leads the air out of the calorimeter. When the air is escaping through the copper tube it will also heat up the water outside the tube. The temperature of the water allows for calculating calorie content of the fuel.

Procedure

The Calorific value of the coal in digital bomb calorimeter can be calculated by five steps:

Step – 1 (Initials)

About 1gm of sample is taken in a crucible. The desired weight can be carried out manually or entered digitally. Two litres of distilled water is filled in the outer jacket.5 to 10 ml of water is placed inside the bomb.

Step -2 (Connection of Igniting Wires)

The sample (powder form) of nearly 1gm is placed in the crucible in the bomb by the help of tripod stand. The two electrodes are connected by nichrome wire touching the coal sample. The bomb is now tightened by the lid.

Fig. No.4.3.2 Oxygen Filling in Bomb Calorimeter

Step – 3 Filling of Oxygen

After tightening the lid of the bomb, oxygen is to be filled into it. It takes 1 minute to fill desired amount oxygen in the bomb. It is filled into the bomb by connecting it into the gas pipe socket of the bomb head

and oxygen cock to the cylinder. The cock is then unscrewed to fill the oxygen of 420 psi (400 – 450).

Step -4 Run of program

The bomb is placed inside the outer jacket which gets immersed in distilled water. The electrodes are fitted to the bomb before the cover of the bomb is to be shut down. Sufficient care is to be taken to avoid the contact of stirrer to the bomb. The device is now ready to run which on running will give us the result of calorific value and temperature rise of coal.

Step -5 Reaction

The whole bomb is now pressurized with excess pure oxygen (typically at 30atm) which contains a weighed mass of a sample (1-1.5 g) and a small fixed amount of water (to saturate the internal atmosphere, thus ensuring that all water produced is liquid, and removing the need to include enthalpy of vaporization in calculations), is submerged under a known volume of water (2 Lt.) before the charge is electrically ignited. The bomb, with the known mass of the sample and oxygen, form a closed system does not allows gases to escape during the reaction. The weighted reactant put inside the steel container is then ignited. Energy is released by the combustion and heat flow from this crosses the stainless steel wall, thus raising the temperature of the steel bomb, its contents, and the surrounding water jacket. The temperature change in the water is then accurately measured with a thermometer. This reading, along with a bomb factor (which is dependent on the heat capacity of the metal bomb parts), is used to calculate the energy given out by the sample burn. A small correction is made to account for the electrical energy input, the burning fuse, and acid production (by titration of the residual liquid). After the temperature rise has been measured, the excess pressure in the bomb is released.

Table no 4.3.1 Ultimate Heat Value (UHV) of coal and its grade

Sl No.	Sample	Ultimate Heat Value(Kcal/Kg)	Grade
1.	MCL1	5467.25	C
2.	NECL1	8152.73	A
3.	SECL1	3900.95	E
4.	WCL1	5555.57	C
5.	SCCL1	4417.07	D
6.	BCCL1	5015.99	C
7.	SECL2	4731.02	D
8.	MCL2	3271.67	F
9.	MCL3	3764.882	E
10.	MCL4	4926.25	D

Table no 4.3.2 Gross Calorific Value (GCV) of coal and its grade

Sl No.	Sample	Gross Calorific Value(Kcal/Kg)	Grade
1.	MCL1	5574.3665	G6
2.	NECL1	7167.3499	G1
3.	SECL1	3946.8717	G12
4.	WCL1	6122.5100	G4
5.	SCCL1	5071.3672	G8
6.	BCCL1	6049.2439	G5
7.	SECL2	5510.1490	G6
8.	MCL2	4574.2311	G10
9.	MCL3	4879.8758	G9
10.	MCL3	3335.3568	G14

4.4. Crossing Point Temperature

It refers to the minimum temperature at which the coal temperature coincides with that of the bath temperature. This method is primarily used in India for determination of liability of coal samples towards spontaneous heating.

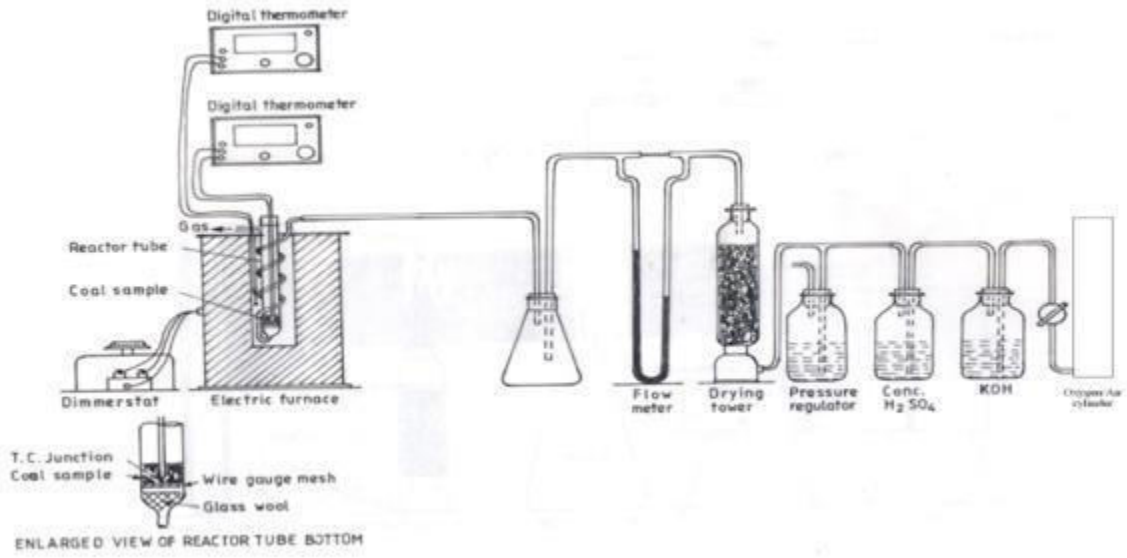


Fig no 4.4.1 Schematic layout of Crossing Point Temperature Apparatus

Experimental procedure

In this method initially coal sample is prepared of size -212 micron. Next to that 4 gram of coal sample was taken and was placed inside a helical test tube over some glass wool initially placed inside the tube. Then the helical glass tube was place inside the furnace and one end of the reaction tube was connected to a valve which supplies constant oxygen flow to the reaction tube at a rate of 80ml/min. Following it the reaction tube was placed inside the air bath furnace and a constant heating rate of 1 degree Celsius rise per min was maintained via a rheostat. Continuous readings were noted of the coal and the bath temperature at interval of 3-4 minutes and finally the experiment is stopped when the coal temperature crosses the bath temperature. Same

procedure was applied for all the 8 samples and the liability to spontaneous heating and the risk rating was determined.

(Mahadevan et al, 1985) proposed a new Liability Index or MR Index after analysing several CPT curves. He divided the heating curve into 3 stages.

The 1st stage was considered up to the point of inflextion (up to a point at which the rate of heating rapidly increased called the inflextion point).

The 2nd stage started from the inflexion point and ended at the Crossing Point Temperature.

The 3rd stage was considered to start from the crossing point temperature and ended at active combustion.

$$\text{Liability Index} = \frac{\text{Heating Rate at CPT} * \text{Time taken to reach the Inflexion Point} * 10}{\text{Time taken to reach the CPT} * \text{Avg. Heating rate between the IP and CP}}$$

The risk rating with respect to the liability index:

Table no 4.4.1 Liability Index (Mahadevan et al., 1985)

Liability Index	**Risk Rating**
0-10	low
10-20	Medium
>20	High

Table no 4.4.2. Classification of CPT (Mahadevan et al., 1985)

CPT (°C)	Risk Rating
120-140	Highly susceptible
140-160	Moderately susceptible
>160	Poorly susceptible

WITS-EHAC Index (Uludag, 2007) of self- heating liability of coal is calculated from the following formula:

Area of the triangle= 0.5* Stage 2 slope *$\frac{1}{Crossing\ point}$*1000

Table no 4.4.3 Crossing Point Temperature, Liability Index, WITS-EHAS and its Risk Rating.

Sl No.	Sample	CPT (°C)	Risk Rating	Liability Index	Risk Rating	WITS-EHAC
1.	MCL1	159	Moderately susceptible	18.39	Medium	4.77
2.	NECL1	193	Poorly susceptible	8.47	Low	3.435
3.	SECL1	161	Poorly susceptible	6.18	Low	3.86
4.	WCL1	155	Moderately susceptible	11.27	Medium	3.87
5.	SCCL1	126	Highly susceptible	10.09	Medium	4.55
6.	BCCL1	222	Poorly susceptible	7.06	Low	2.34
7.	SECL1	158	Moderately susceptible	15.64	Medium	4.101
8.	MCL2	160	Moderately susceptible	14.17	Medium	4.71
9.	MCL3	164	Poorly susceptible	12.54	Medium	4.46
10.	MCL4	143	Moderately susceptible	13.67	Medium	4.32

CPT Curves of Coal Samples

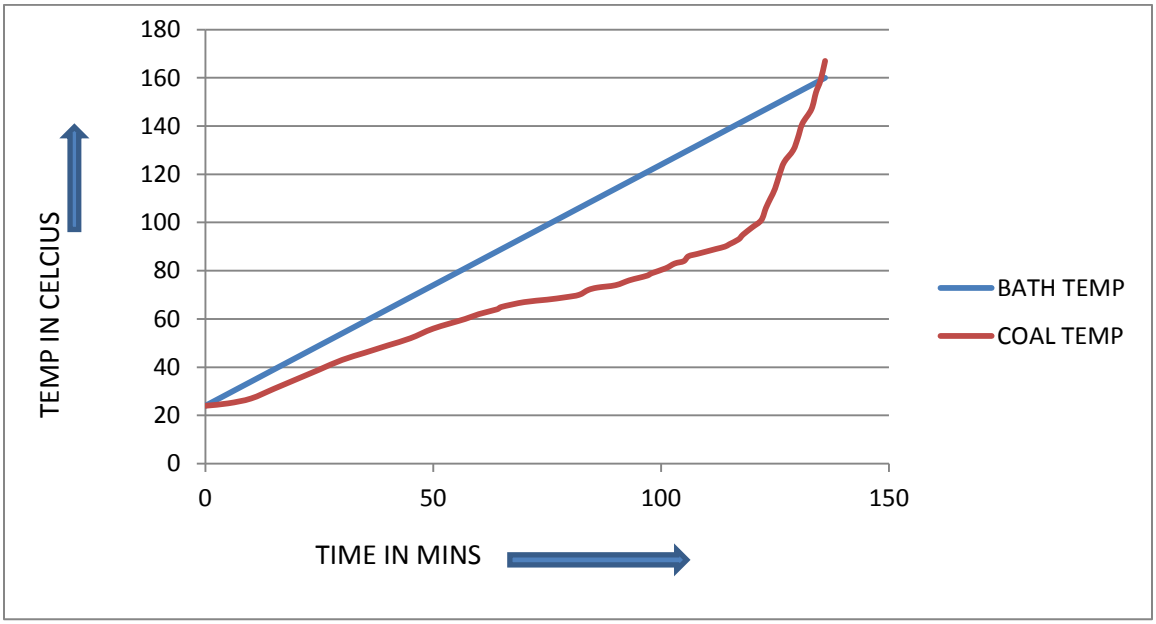


Fig no 4.4.2 CPT Curve for Sample MCL1

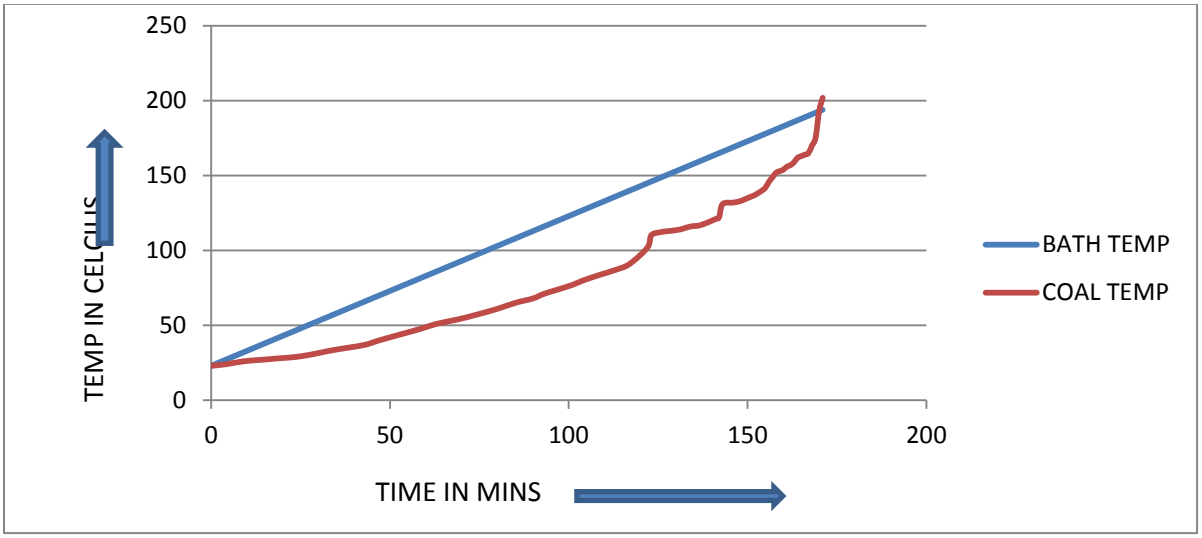


Fig no 4.4.3 CPT Curve for Sample NECL1

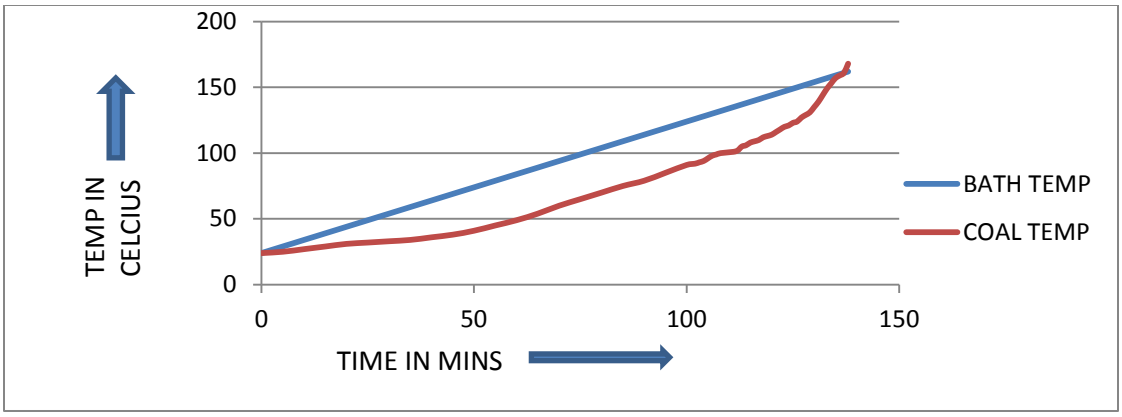


Fig no 4.4.4 CPT Curve for Sample SECL1

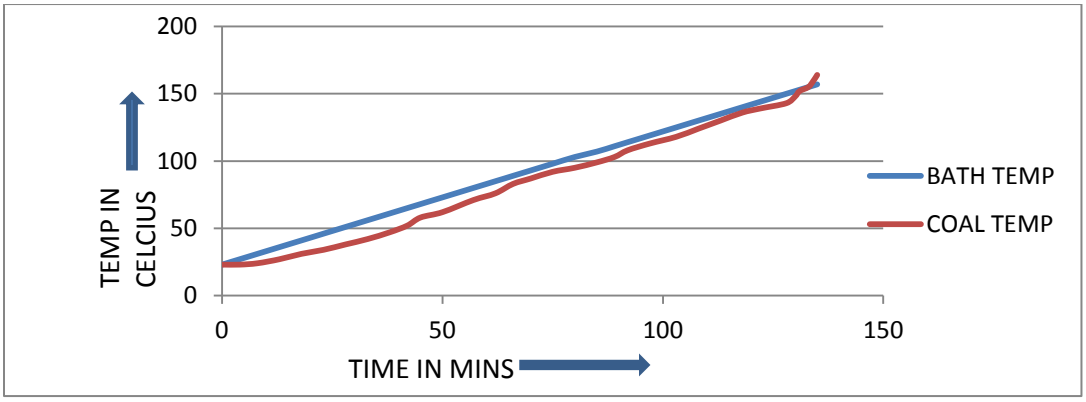


Fig no 4.4.5 CPT Curve for Sample WCL1

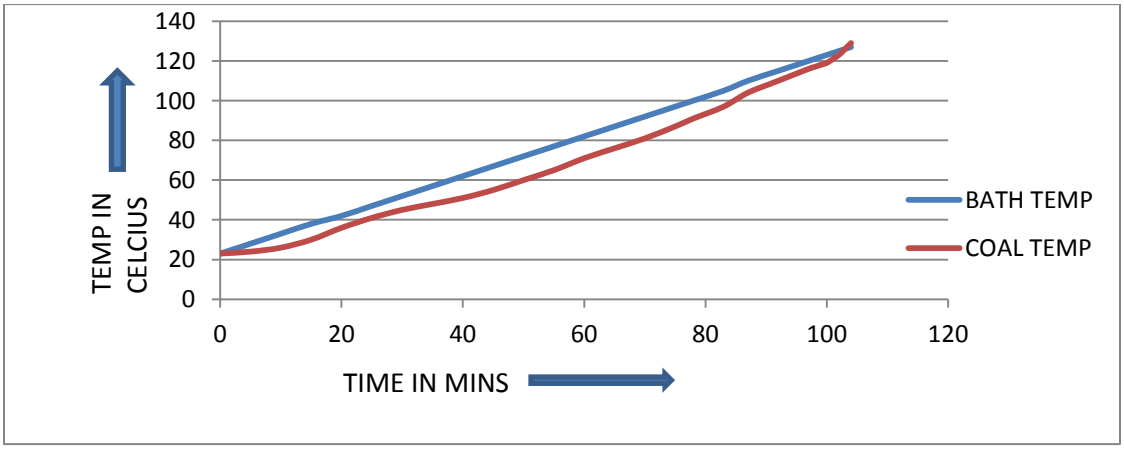


Fig no 4.4.6 CPT Curve for Sample SCCL1

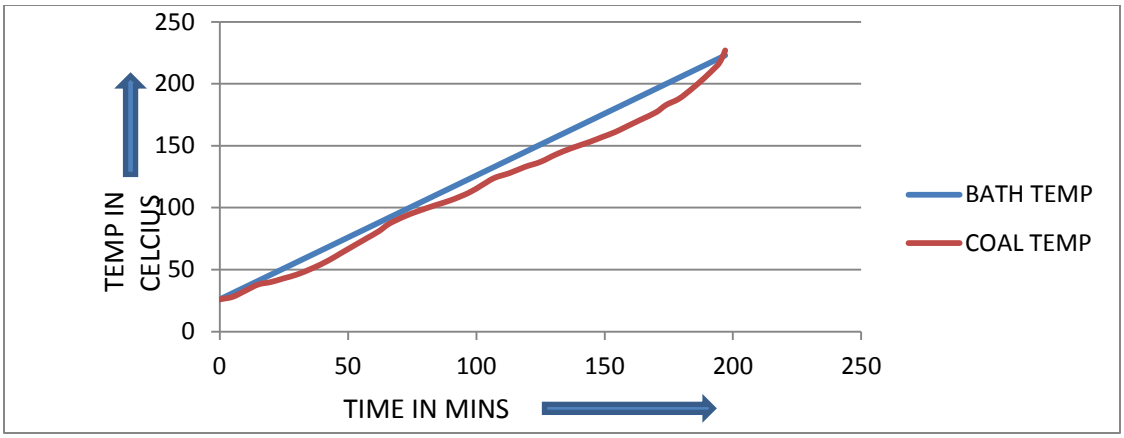


Fig no 4.4.7CPT Curve for Sample BCCL1

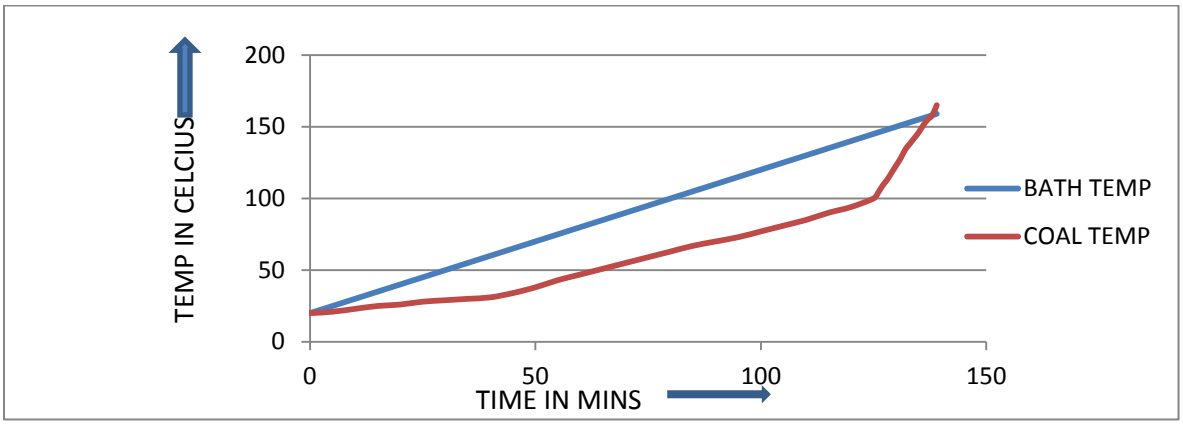


Fig no 4.4.8 CPT Curve for Sample SECL2

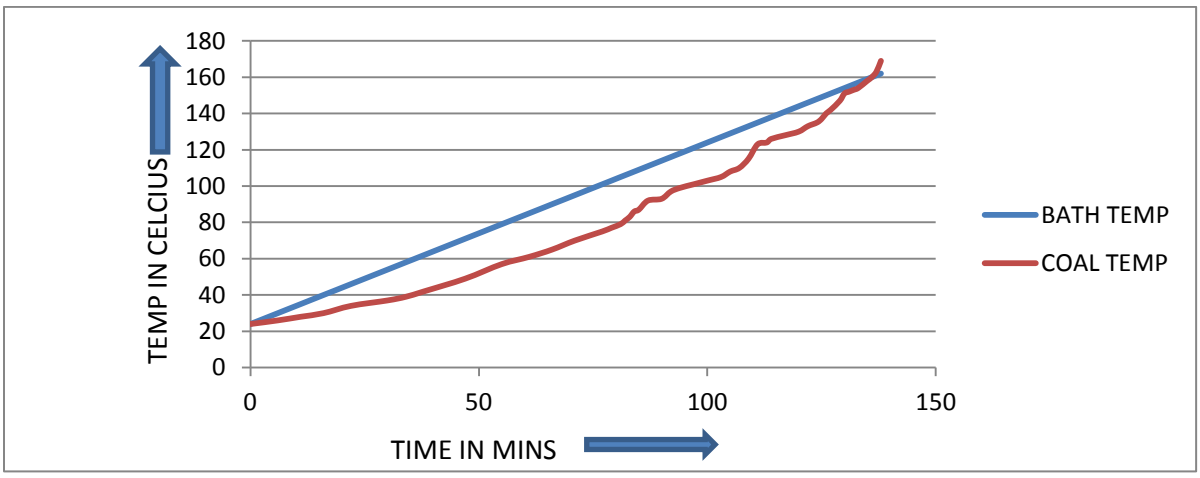


Fig no 4.4.9 CPT Curve for Sample MCL2

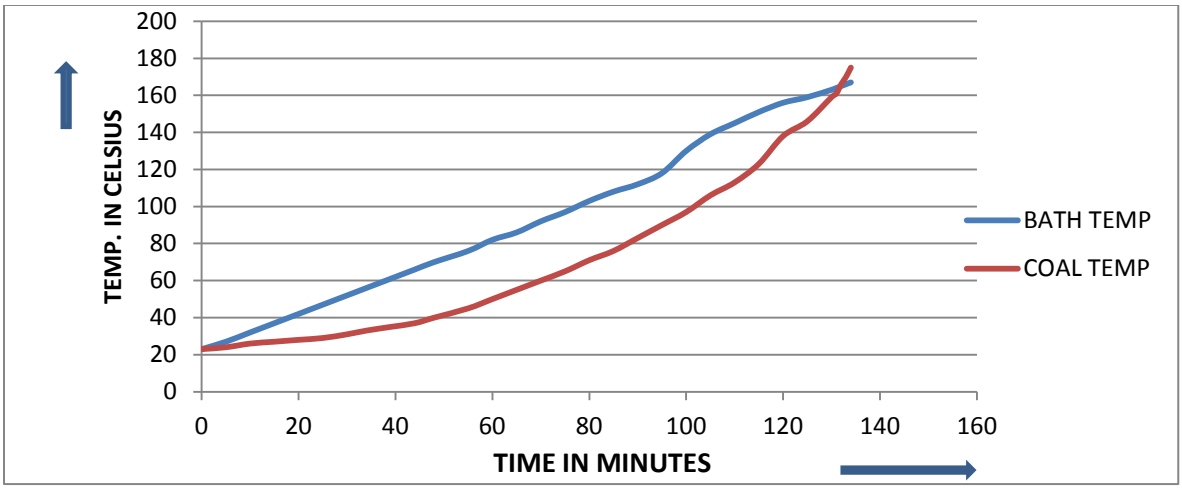


Fig no 4.4.10 CPT Curve for Sample MCL3

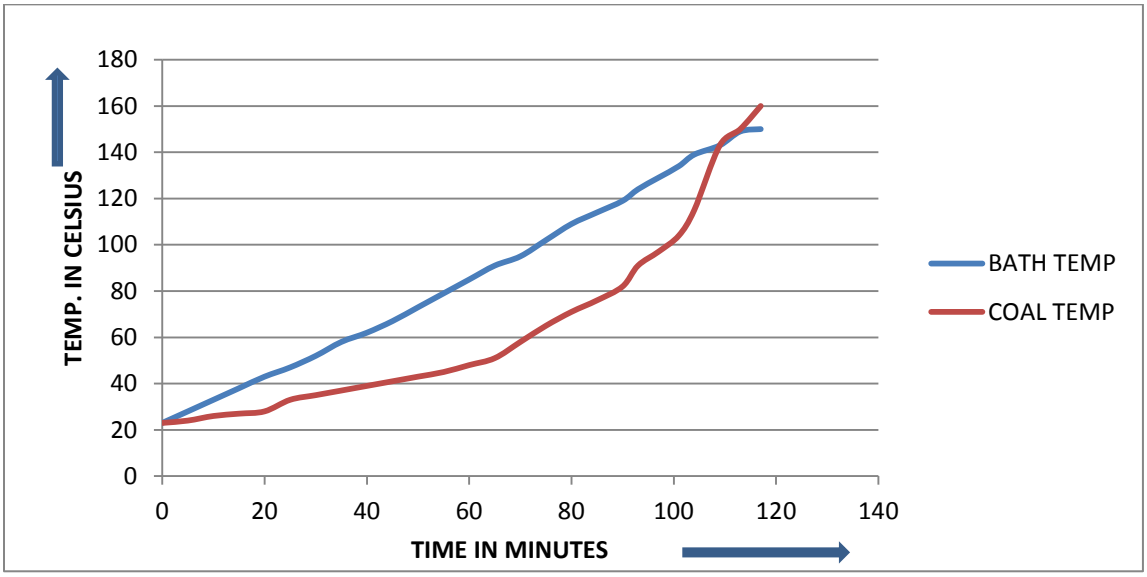


Fig no 4.4.11CPT Curve for Sample MCL4

4.5. Flammability Temperature

Flammability basically refers to the minimum temperature at which coal ignites. Here the concept is based on the ideology that flammability temperature of a coal sample decreases with increasing oxidation of coal and this concept of difference between the ignition temperature of coal after and before oxidation can be used as a tool to determine the liability of coal samples to

spontaneous combustion. It is used to determine the efficiency of coal dusting . The experimental set up consists of a vertical tubular furnace of internal diameter 50 mm, length 300 mm which is open at both ends having a a dust dispersing unit along a solenoid valve and a reservoir for air. It also consists of a mercury manometer, a drying tower and an aspirator bulb. Coal dust sample is kept in the helical dust disperser. Air at an pressure of 50 mm of Hg from the reservoir is made to pass through the disperser in order to disperse the powdered coal forming a uniform air-dust mixture within the furnace. The minimum temperature at which this mixture catches fire, which is indicated by the appearance of flame coming out of the bottom of the tubular furnace is known as the flammability temperature of the coal dust.

Experimental Procedure:

1) 200 mg sample of coal having mesh size -72 micron (-200 mesh BSS) was placed in a helical tube.

2) The aspirator bulb was squeezed continuously to make the mercury column difference maintained at a pressure of 80 mm.

3) After switching on the solenoid valve, at the desired temperature of furnace, the air passes at a very fast rate and carries away the coal dust along with it to show signs of flame, smoke or spark.

4) This operation is carried out at a difference of every 5˚C.

5) If flame appears then in order to determine the exact temperature experiment is carried out in lower temperature range or else we move on to high temperature range. But in all it's a hit and trial method of identifying the exact Flammability Temperature. Precaution should be taken to pre dry the circulated air in order to avoid error due to humidity.

Fig no 4.5.1 Schematic Layout of Flammability Apparatus

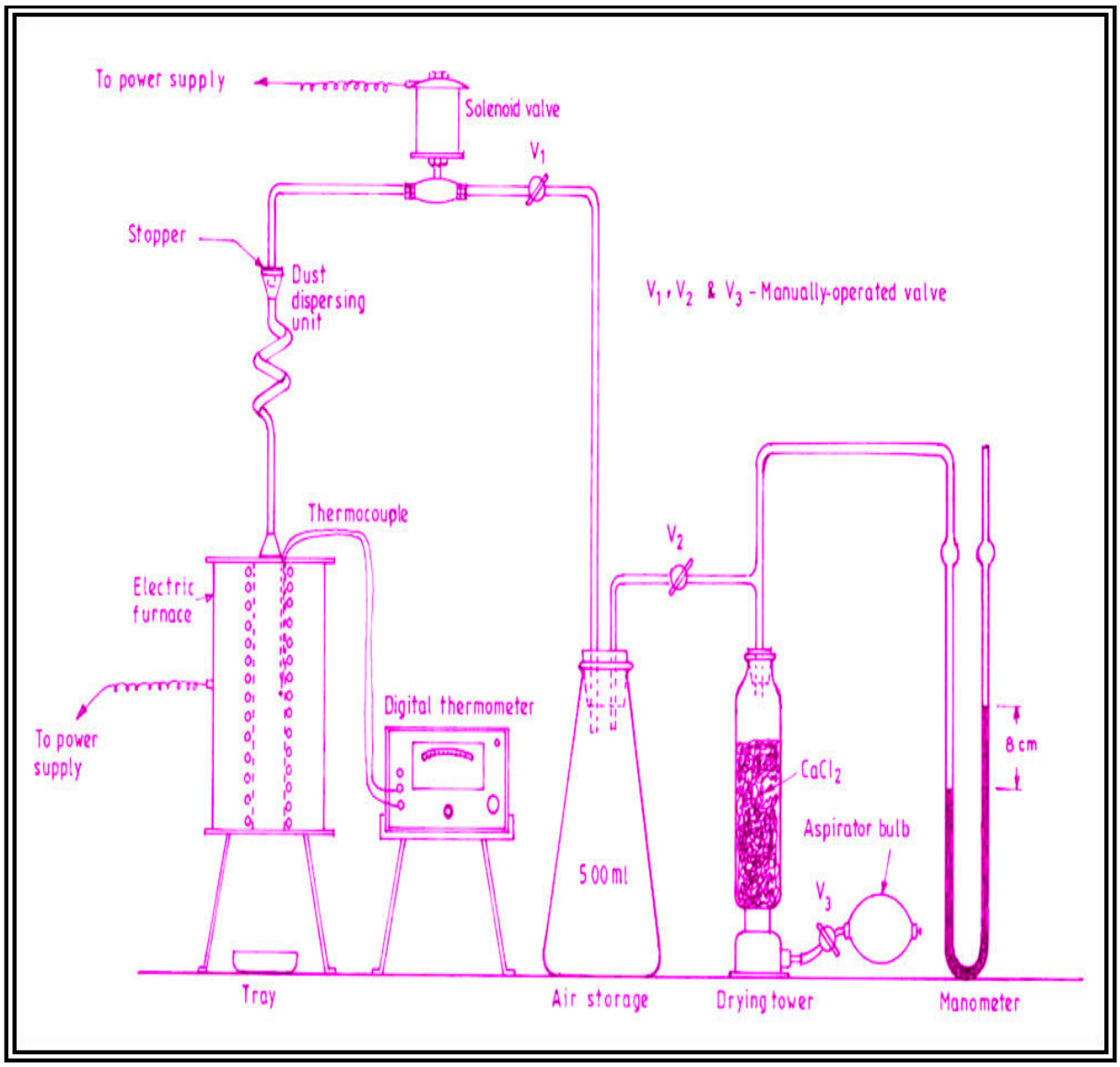


Table no 4.5.1 Flammability Temperature of the Coal Samples

Sl No.	Sample	Flammability Temperature(°C)
1.	MCL1	505
2.	NECL1	500
3.	SECL1	540
4.	WCL1	515
5.	SCCL1	415
6.	BCCL1	450
7.	SECL2	545
8.	MCL2	530
9.	MCL3	500
10.	MCL4	560

4.6 Wet Oxidation Potential Analysis:

A coal molecule constitutes two parts:

1. The condensed aromatic structure which in totally resistant to oxidation.

2. The hydro-aromatic structure or the aliphatic (open chain) part those are highly prone to oxidation.

Basically presence of hydroxyl groups in the aromatic part adds up to the reactivity rate of the coal structure and oxidises it faster. Above mentioned reason is one of the prime cause of fast oxidation of low rank coals. In addition to that also low rank coals have lower degree of condensation of aromatic structure in it. On oxidation low rank coals produce huge amount of aliphatic acids mainly formed from base aliphatic presence in low rank coals. But higher rank

coals have structure similar to that of graphite which helps it in formation of aromatics rather than aliphatic. Hence, lower the potential difference lower is the liability of coal towards spontaneous heating.

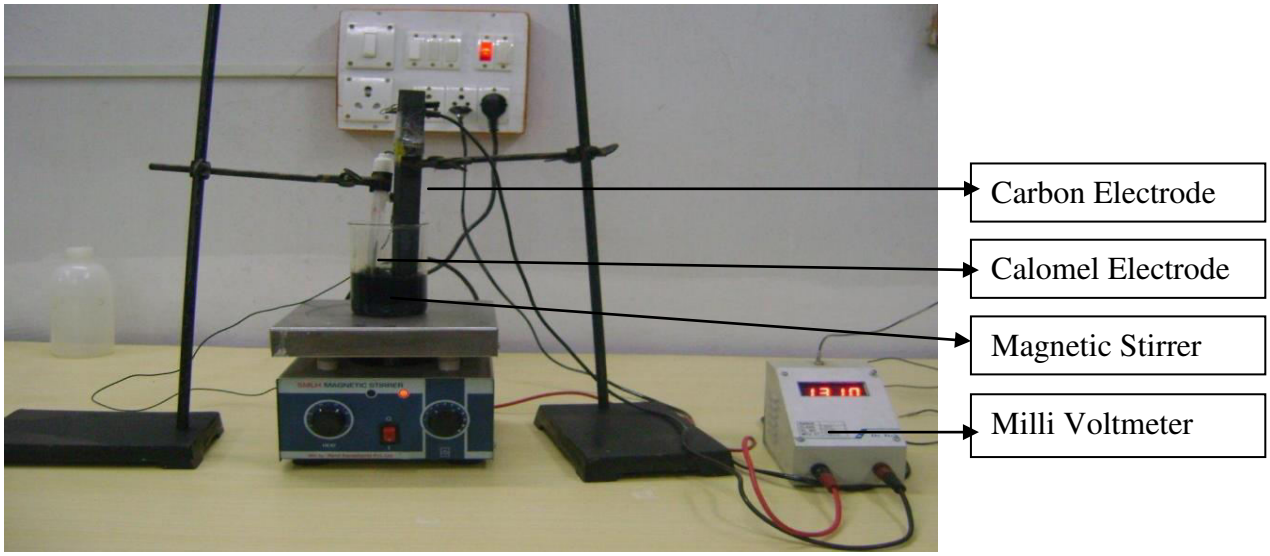


Fig no 4.6.1 Experimental set up of Wet Oxidation Potential Apparatus

Experimental Procedure

Initially a solution of 100ml mixture was formed by mixing 0.1 N solutions of potassium permanganate and 1N potassium hydroxide. Then this solution was placed inside the beaker and the magnetic stirrer is allowed to stir smoothly the solution. Then 0.5 gram of coal sample of 212 micron size was weighed and kept aside. Next to that e carbon and calomel electrodes were dropped into the solution and the mill voltmeter was turned on. After that the weighed coal sample was put inside the solution and the resultant coal oxidation suspension was continuously stirred by the magnetic stirrer and the potential difference (EMF) between the carbon and calomel electrode was noted down within every 1 minute up to 30 minutes until the potential difference value becomes constant. The higher the Potential Difference, the higher the liability towards spontaneous heating.

Table no 4.6.1 –Wet Oxidation Potential Difference of the coal samples

Sl. No.	Sample	Wet Oxidation Potential Difference(mV)
1.	MCL1	65.2
2.	NEC1	22.4
3.	SECL1	43.4
4.	WCL1	48
5.	SCCL1	73
6.	BCCL1	17.4
7.	SECL2	36.3
8.	MCL2	56.3
9.	MCL3	82.1
10.	MCL4	50.9

Wet Oxidation Curves of Samples

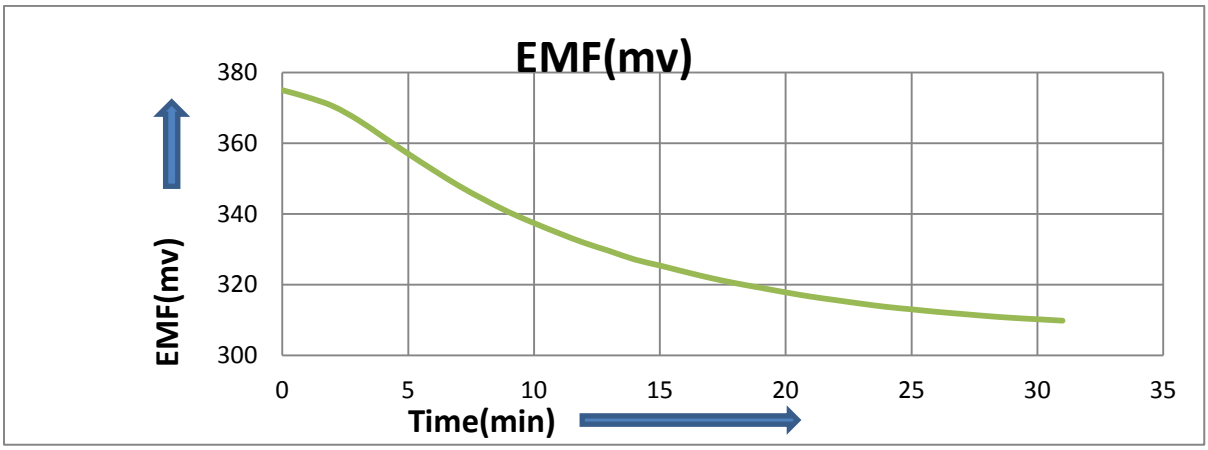


Fig no 4.6.2 Wet Oxidation Curve for Sample MCL1

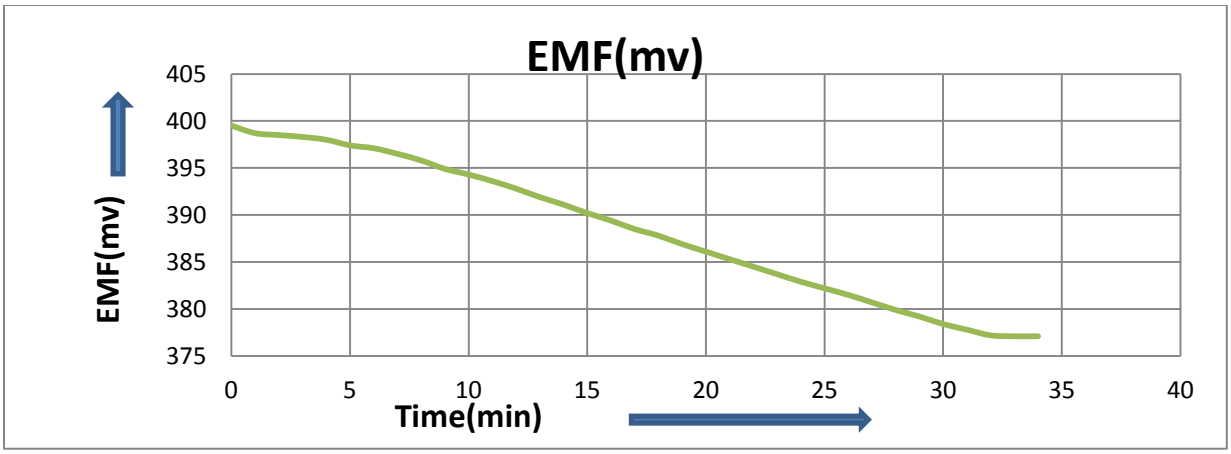


Fig no 4.6.3 Wet Oxidation Curve for Sample NECL1

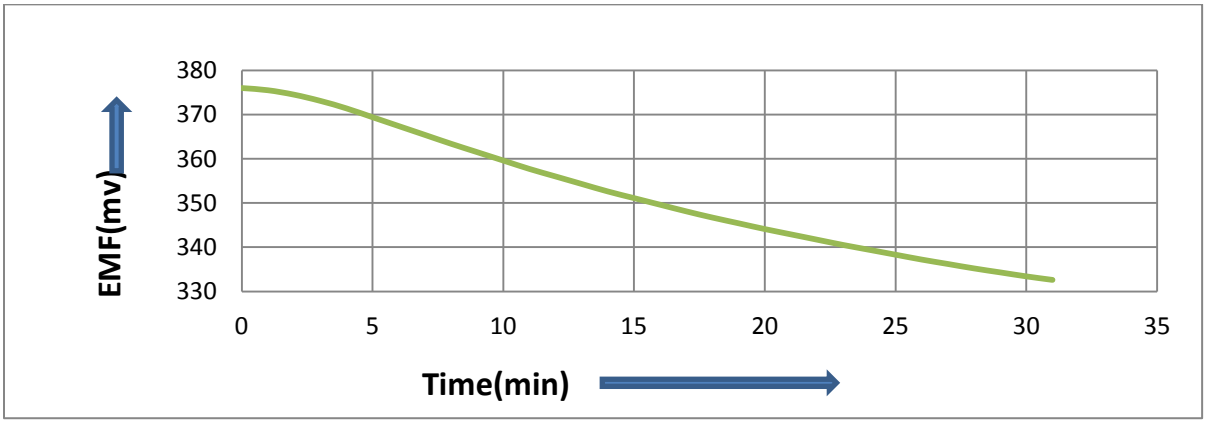


Fig no.4.6.4 Wet Oxidation Curve for Sample SECL1

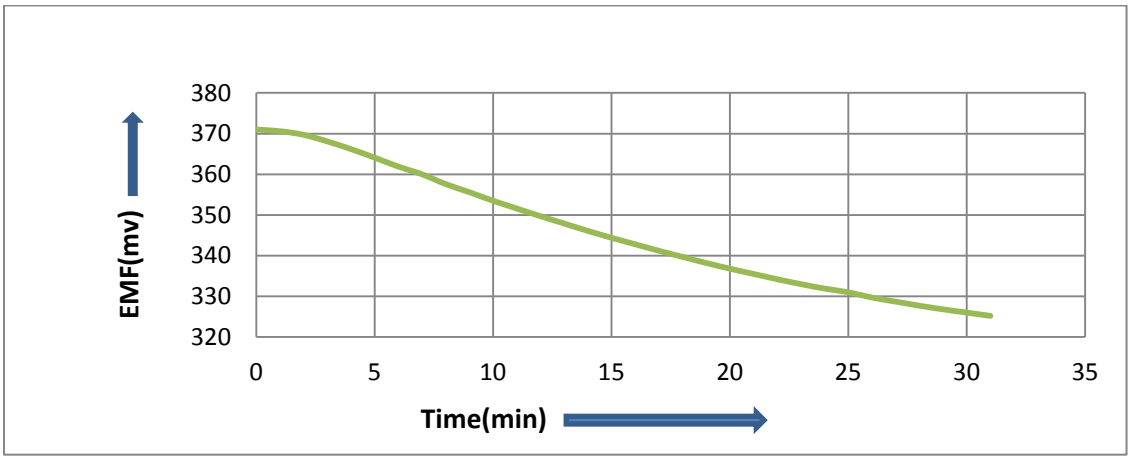


Fig no.4.6.5 Wet Oxidation Curve for Sample WCL1

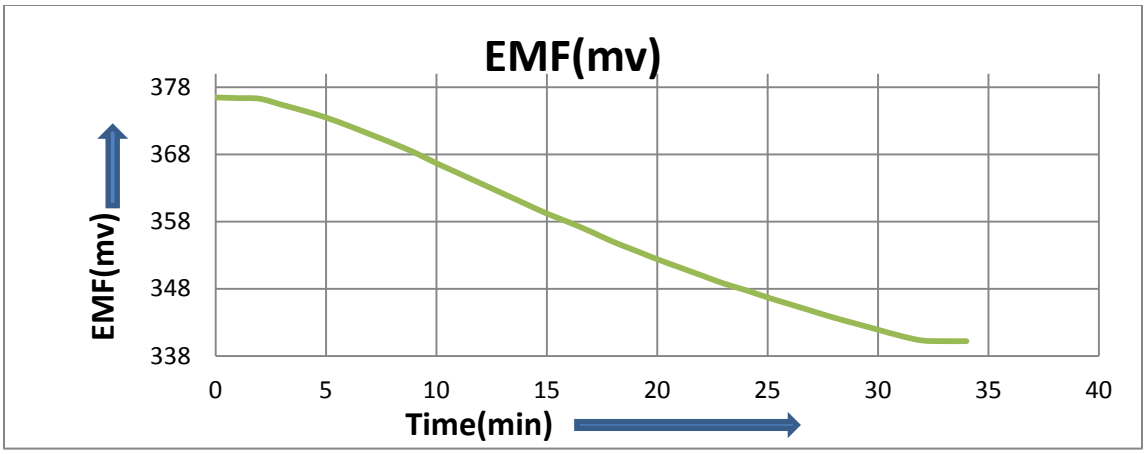


Fig no.4.6.6 Wet Oxidation Curve for Sample SCCL1

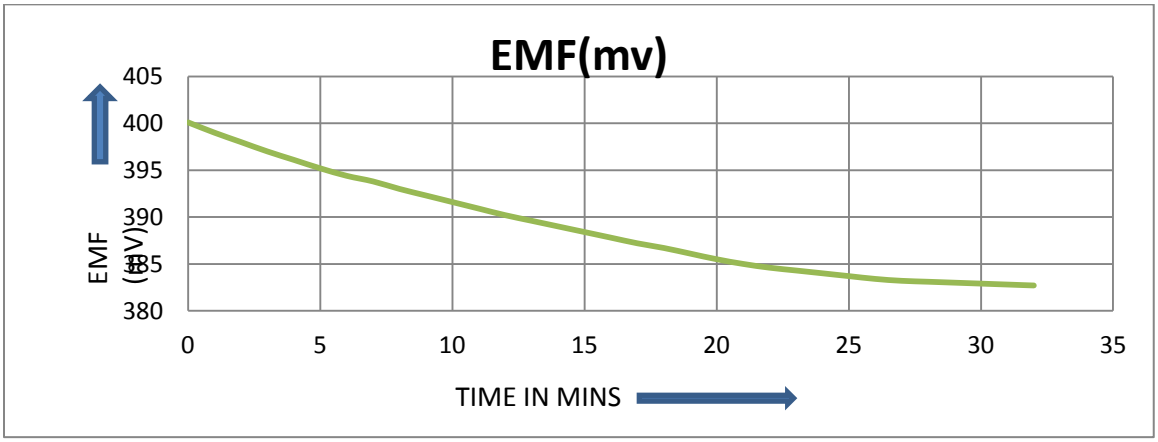


Fig no 4.6.7 Wet Oxidation Curve for Sample BCCL1

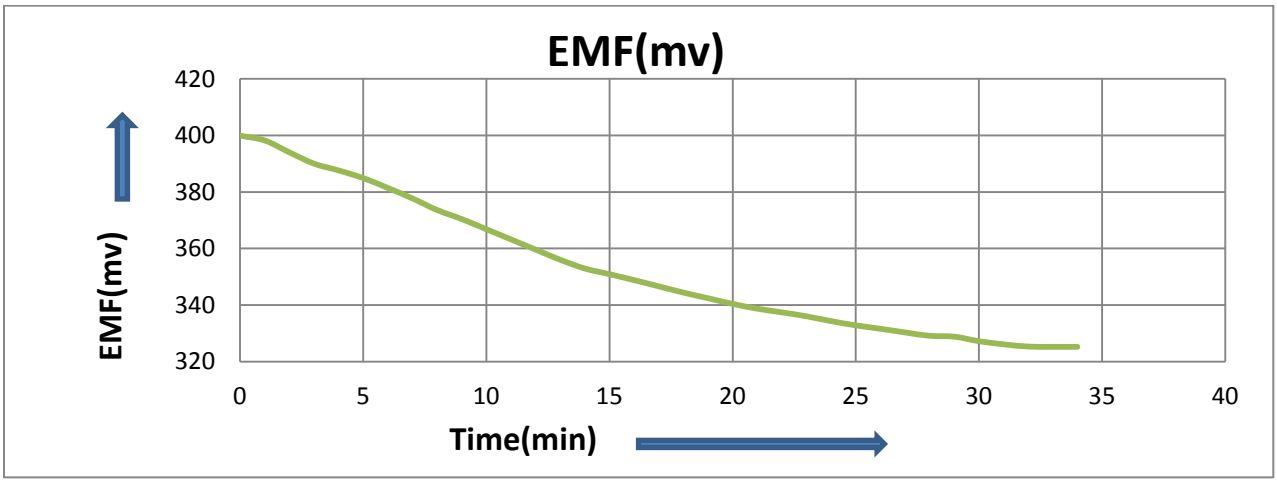


Fig No. 4.6.8 Wet Oxidation Curve for Sample SECL2

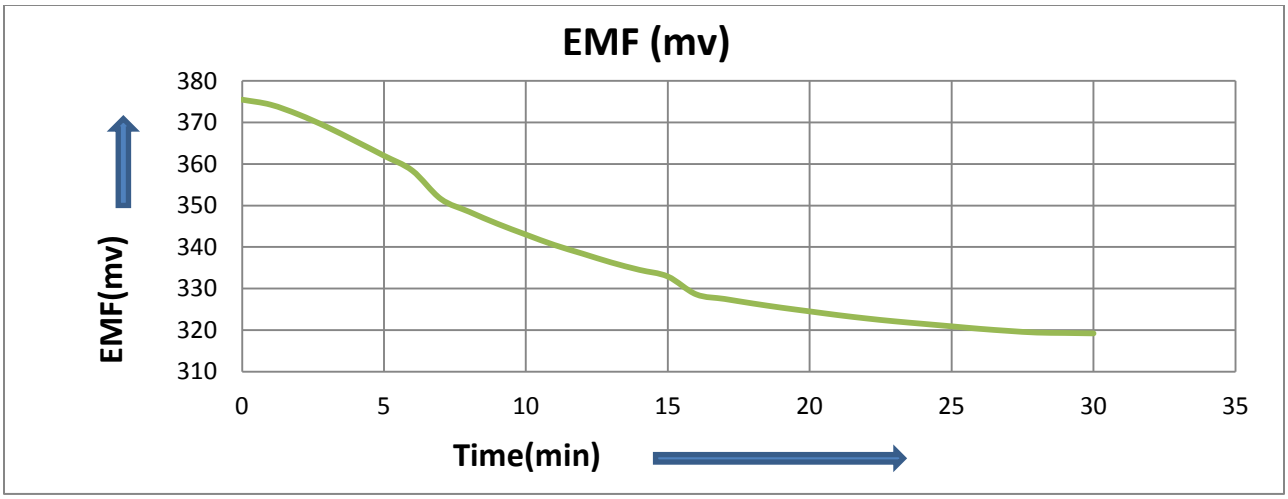


Fig no 4.6.9 Wet Oxidation Curve for Sample MCL2

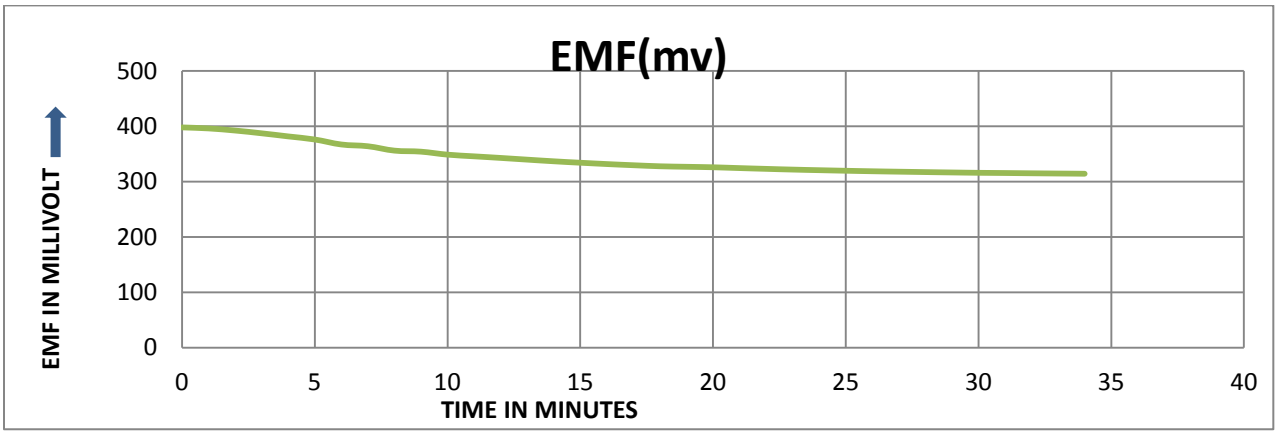


Fig no 4.6.10 Wet Oxidation Curve for Sample MCL3

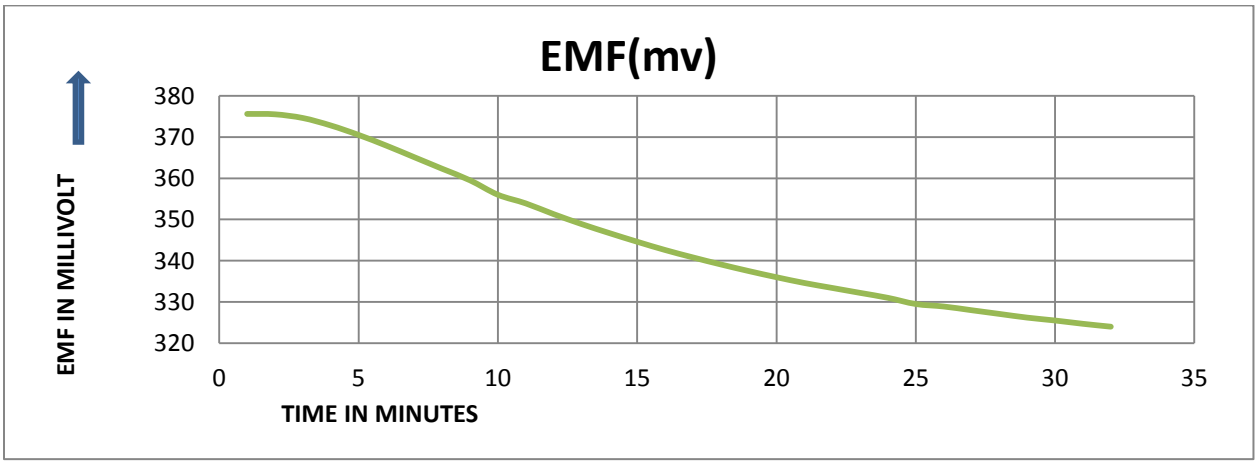


Fig no 4.6.11 Wet Oxidation Curve for Sample MCL4

Chapter 5

Protective Measures

Protective Measures for spoil pile

Protective Measures for Stock pile

Protective measures during Mining

5. Protective Measures of Spontaneous Combustion of coal

Spontaneous combustion of coal is a common concern within the coal stockyard of thermal power plants due to the direct effect that energy losses have on financial performance. As coal is the primary fuel for a thermal power plant, adequate emphasis needs to be given for its proper handling and storage. It's also essential because of related safety and environmental implications of spontaneous combustion of coal. The problem is a natural phenomenon that is aggravated by improper management of coal. A lot of research has been done on spontaneous combustion of coal but still there is a lack of a comprehensive approach which can be applied to deal with the problem.

The costs involved due to the energy and quantity loss of coal as an outcome of self combustion have been well established in the past and shown to be considerable. Also accelerated weathering due to prolonged self heating leads to loss of the gross calorific value of coal, and is considerable. Therefore, a comprehensive approach to control spontaneous combustion of coal has to be taken and can be categorized into three fields.

Protective Measures of spontaneous combustion of coal in coal spoil piles.

Protective Measures of spontaneous combustion in stock piles.

Protective Measures of spontaneous combustion of coal during mining.

5.1 Protective Measures for spoil pile

5.1.1 Introduction

The term "spoil" is also used to refer to material removed when digging a foundation, tunnel, or other large excavation. These materials may be ordinary soil and rocks, or may be heavily contaminated with chemical waste. A spoil pile is a pile built of accumulated spoil - the overburden or other waste rock removed during coal and ore mining. These waste materials are typically composed of shale, as well as smaller quantities of carboniferous sandstone and various other residues. In spoil piles it is normally unrealistic to remove the fuel and similarly, removal of heat by ventilation or water sprays, is usually impractical. Self heating results when the rate at which heat is generated within a structure is greater than the rate at which the heat can be lost to the environment. In order to provide quantitative descriptions of self heating it is necessary to quantify the heat generation and loss processes. In spoil piles there are four major sources of heat.

1) Direct oxidation of coal.
2) Oxidation of other carbonaceous strata.
3) Oxidation of reactive pyrite commonly associated with coal seams.
4) Condensation of water vapour within a porous structure (due to changes in relative humidity) can release considerable heat and aid self heating.

The reactivity of the materials in spoil varies considerably. Coal is the most reactive material whereas materials that contain no carbon, e.g. sandstone, rocks and soil and clay, are inert. In general, the reactivity of a material depends on its carbon content. Large amounts of reactive carbonaceous materials in spoil increases the risk of spontaneous combustion.

5.1.2 Problems of Uncontrolled Spontaneous Combustion

Spontaneous combustion in spoil pile occurs accidently or deliberately. Spontaneous combustion in spoil piles poses a number of potentially serious safety and environmental problems which includes:

1. Acute safety hazards to mine personnel working near actively burning ground.

2. Toxic emissions such as particulates, CO, SO_2, H_2S, polynuclear aromatic hydrocarbons and volatile organic compounds.

3. Greenhouse gas emissions of Carbon dioxide.

4. Methane Emission and Odours.

5. Destabilisation of spoil piles and long-term problems with rehabilitation.

Figure No. 5.1.2.1Local Fire in Shanxi China

(Burning under a house)

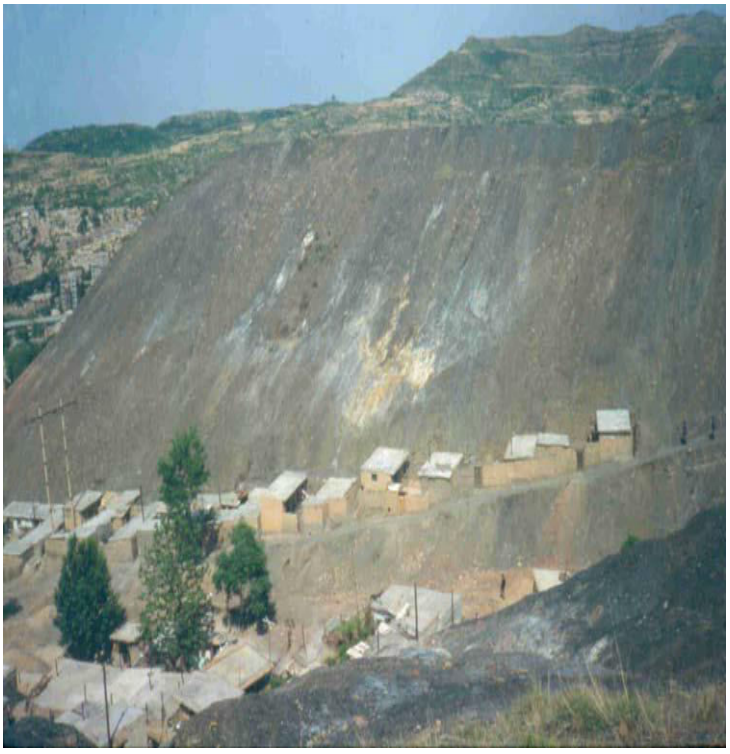


Figure No. 5.1.2.2 Burning Pile in Shanxi China

The hazardous impact of spontaneous combustion of spoil pile is going on increasing day by day. So it becomes necessary to find some preventive methods to avoid it. Many methods such as flooding, blanketing, slurry injection, compacting, loading out, and sealing have been attempted in the past to control spontaneous combustion but still there is need of a reliable

method in preventing it.

5.1.3 Prediction of Self Heating

The rate of heat generation by coal and carbonaceous shapes can be used as the basis for the development of a method for predicting self heating. The relative rates of heat generation and dissipation for a spoil pile can be summarised under these equations.

Heat Balance Equation

$$\sigma\frac{\partial T}{\partial t} + \rho_a C_a \nu.\nabla T = k\nabla^2 T + Q_\circ$$

Where, T is temperature, t as time, σ is the composite thermal capacity of the medium, k is the composite thermal conductivity of the medium, ρ_a and C_a is the density and heat capacity of air, ν is the velocity of air and $Q_\circ$ is the total rate of heat generation and includes the heat of water condensation or evaporation as well as oxidation.

The first term gives the rate at which heat is accumulated, the second gives the rate at which heat is transported by the gas velocity ν, the third term gives the rate at which heat is conducted by the coal matrix and the fourth term $Q_\circ$ is the rate at which heat is generated or lost by the spoil.

Mass Balance Equation for Gas(Oxygen and Watervapour)

$$\epsilon\frac{\partial B}{\partial t} + \nu.\nabla B = D_b\nabla^2 B - M$$

Where ϵ is the spoil voidage, B is the concentration of gas (oxygen and water vapour in the void) at time t, D_b as the effective reaction coefficient, M the rate of depletion of

oxygen through reaction or the rate of depletion or production of water vapour which may condense or evaporate.

Momentum Balance Equation

$$\nu = \frac{k}{\mu}(-\nabla P + \rho_a g)$$

Where P is the air pressure, k is the specific permeability, μ is the dynamic viscosity of air and g is the acceleration due to gravity.

The momentum balance equation is deduced from Darcy's law for fluid flow in porous medium. The first term describes the flow due to pressure gradient while second term describes the buoyancy due to gas density changes with temperature.

Continuity Balance Equation

$$\nabla . \nu = 0$$

It assumes the validity of boussinesq approximation. This approximation essentially states that the temperature variation of fluid property. In general the thermal conductivity depends on the materials, the packing of the spoil pile and the moisture content. The variation of gas density with temperature is only taken into account in the term of buoyancy. The extent to which convection is important depends on the permeability of the spoil pile and on the external pressure distribution. In spoil piles it is the result of barometric pressure changes and the effect of winds. The numerical values for the permeability of spoil pile are assumed. The above equations have been applied to coal spoil piles. The model for spoil allows for the influence of differing voidages through the depth of the pile as well as the presence of fractures which can act as conduits and provide access of oxygen deep within spoil piles.

5.1.4 Protective Measures

Spontaneous combustion is best prevented by carefully managing the placement of high carbon content material within spoil piles. It is therefore important that the overall management plan for a mine include appropriate measures for dealing with spontaneous combustion and identify reactive materials and inert materials that can be used as cover layers.

Formation of Barrier

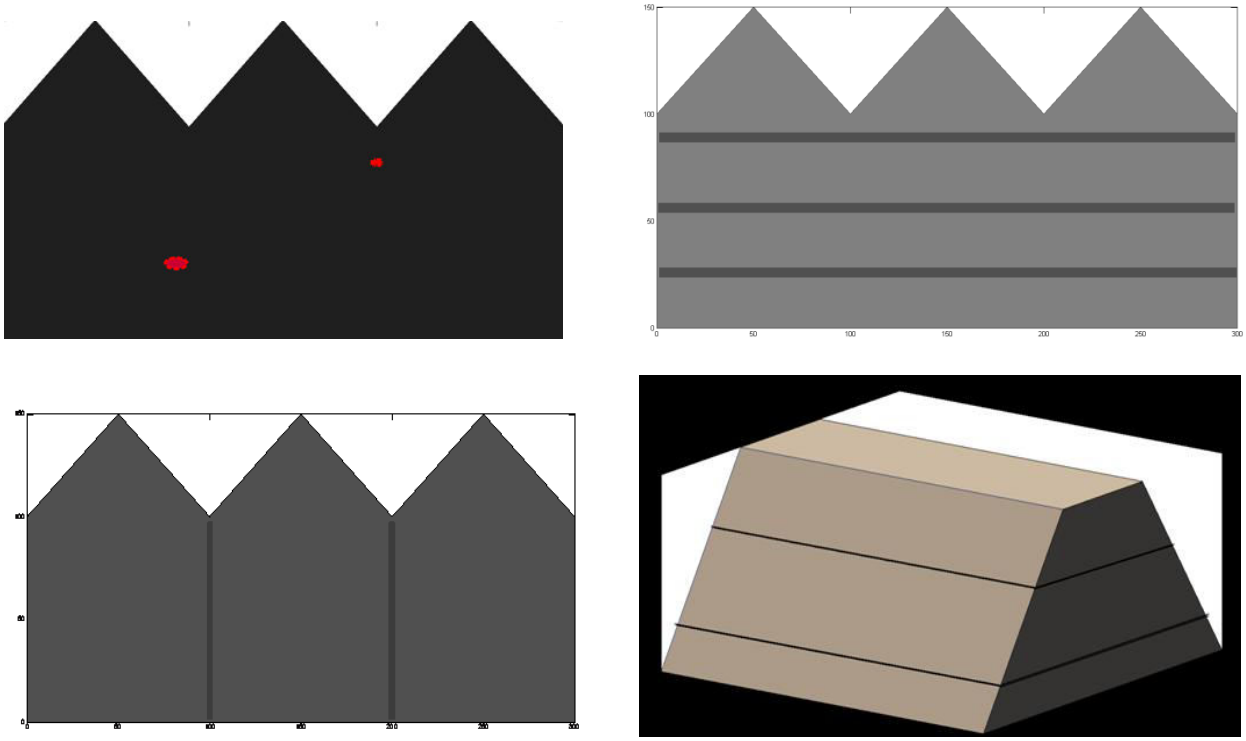


Figure No. 5.1.4.1 Spontaneous combustion in spoil pile

Spoil piles should be designed so that the reactive materials are isolated within thick non-reactive layers which prevent the ingress of oxygen. The thickness of the inert layers required depends on the inert material being used. For clay, layers between 1 and 2 m thick may be enough to stop self-heating whereas for more porous material such as blocky sandstone, much thicker layers of 10 m or more are needed. It is also important to construct spoil piles so that the cover layers are not subject to excessive erosion or other processes that can lead to the formation of cracks and thus allow entry of oxygen. Coal refuse present in low quantity at a place does not cause as much destruction as when it gets connected with combustion element present nearby. This interconnection of coal refuse should be avoided. Horizontal barrier and vertical barrier of mud or non combustible elements can serve as the insulating material for the purpose.

Minimize Dimension

The dimension of the spoil can be restricted within 24 inches which is taken as the optimum to minimize spontaneous combustion. It is not known for sure how deep the pile needs to be before self heating occurs. It is believed that the approximate depth of the pile's insulative layer should be about 24inches, hence the recommendation for pile dimension.

Utilization

Coal refuse can be used as a soil amendment. It can be used for backfilling, conventional excess spoil disposal fills. The residue piles can be utilized as fuel, by which spontaneous combustion can be avoided.

Monitoring

Mines that are prone to spontaneous combustion should have a regular program of inspection of spoil piles, where trained operators seek out the telltale signs. The signs like presence of steam and smoke, surface discolouration and the distinctive odour can act as an indicator of spontaneous combustion.

The use of cover layer and fly ash to prevent spontaneous combustion

Most strategies for control and prevention of spontaneous combustion focus on removing oxygen or preventing its access to the fuel. This is usually best accomplished by the applying cover layers of inert material which reduce the rate at which oxygen can penetrate the spoil pile. The best cover materials are clays which can retain residual moisture. Moisture is important because it acts to seal off oxygen pathways, thus preventing the oxidation reaction from proceeding. Nowadays researches are made on fly ash to act as the insulating material to reduce susceptibility of spontaneous combustion for spoil pile.

5.1.5 Conclusion

Self heating in spoil piles is mainly due to the interaction of coal and carbonaceous spoil materials with oxygen and water. Though considerable progress has been made in recent years on the understanding and modelling of spontaneous combustion, the processes involved are sufficiently complex that greater work is required for methods to be developed which will allow accurate predictions of self heating and spontaneous combustion in spoil piles.

5.2 Protective Measures for Stock pile

Introduction

Coal is one of primary fossil fuels adopted in power plants. It is a solid fuel and storable. Accordingly, coal is usually stored for a long time in a coal storage yard before it is transferred to the furnace for combustion or burning. These coal stockpiles are of large scale and are located in a coal storage yard for several months. In the open air, the coal stockpile is exposed to air and coal is oxidized slowly by oxygen. Although atmospheric temperature is low, low-temperature oxidation of coal in the stockpile continues for a long time and finally, it leads to spontaneous ignition followed by rapid combustion. Spontaneous combustion occurs when heat produced by low-temperature reaction of coal with oxygen is not sufficiently dissipated to the surrounding environment. This self-heating of coal stockpile continues to increase temperature of coal and its temperature reaches ignition temperature of coal. As the last step of the process, coal undergoes rapid combustion, which takes place over about 200 °C. This occurs gradually and may take few months depending on the type of coal and surrounding atmosphere. However coal produced cannot be utilized at the same time due to many factors like fluctuation of demand, supply and transporting constraints, poor grade of coal etc. Hence it becomes essential for storage of coal.

Coals are generally stored in stockyard or storage yard. If coals are stored for a longer period of time, it may lead to spontaneous ignition of coal. Spontaneous ignition of coal in a storage yard may result in economic loss and serious hazard in fire safety. The emission from coal combustion in a coal storage yard causes environmental problems. In predicting spontaneous ignition of coal stockpiles, a large scale or full-scale experiment is required because complex scaling effects can't be realized in a small-scale experiment. Generally, spontaneous ignition has not been observed in coal stockpiles with a small scale while

it has been often reported in large-scale experiments. But, a large scale experiment is formidable and spends much expense and time. The preventive measures are of primitive type and needs a better method for storing of coal.

5.2.1 Factors affecting spontaneous ignition of the coal stockpile

There are two main factors affecting spontaneous ignition of the coal stockpile. They are

1. Heat release rate from chemical reaction inside the stockpile.

2. Heat loss rate from the stockpile to the surroundings.

If the heat release rate from chemical reaction inside the stockpile is greater than the heat loss rate from the stockpile to the surroundings, spontaneous ignition is carried out very fast. And, if less than the ignition is induced latter.

5.2.2 Reasons for storage of coal

The reasons for storage of coal are: -

a) Decrease of demand of coal in the market.
b) To meet the consumer's demand without interruption.
c) To produce in mild climate conditions and market in winter.
d) To decrease the moisture content of coal.
e) To feed the thermal power stations continuously with the coal of specified properties.

Problems faced in coal stacks

a) The Problems faced in coal stacks are:
b) Stacked coal is an unprofitable investment and needs supplementary expenses.
c) Coking property and calorific value of coal is decreased as a result of oxidation of coal.
d) Oxidation of coal causes an increase in ignition temperature.
e) Oxidized coal decreases the performance of washing plants.
f) Explosive gas composition may be formed due to storage of coal.

5.2.3 Mechanism of Spontaneous Heating

The transport of the reactants and transport of heat plays a major role in spontaneous heating of coal. Heat is transported away from the sites where it is generated due to temperature gradients. They are mainly through conduction and convection mechanisms. Oxygen and water take part in the heat generating processes and they are also transported by diffusion and convection. Convection in coal piles may be caused by differences in wind pressure at the surface of the pile (forced convection) and differences in temperature between the pile and the surrounding air (free or natural convection.).After many research works it is assumed that natural convection is the primary cause of flow of air within the stockpile. However, wind-driver forced convection cannot be neglected. In fact, it may be the major factor which influences the initial heating of the coal pile.

With the stockpile, oxidation process of coal inside the stockpile passes through a series of steps. First there is formation of coal oxy complex which on availability of oxygen produces hot spot and on further supply of oxygen leads to spontaneous combustion. The temperature field inside

the stockpile evolves with time .In all of spontaneous-ignition cases, hot spot is always formed just below the surface in the edge of the stockpile and it propagates to the center. Air density near the center gets lowered due to temperature rise of air, and air flows upward inside the stockpile. During coal oxidation, mass fraction of O_2 continues to decrease due to chemical reaction and it is nearly consumed out after burning because fuel is rich and O_2 is deficient.

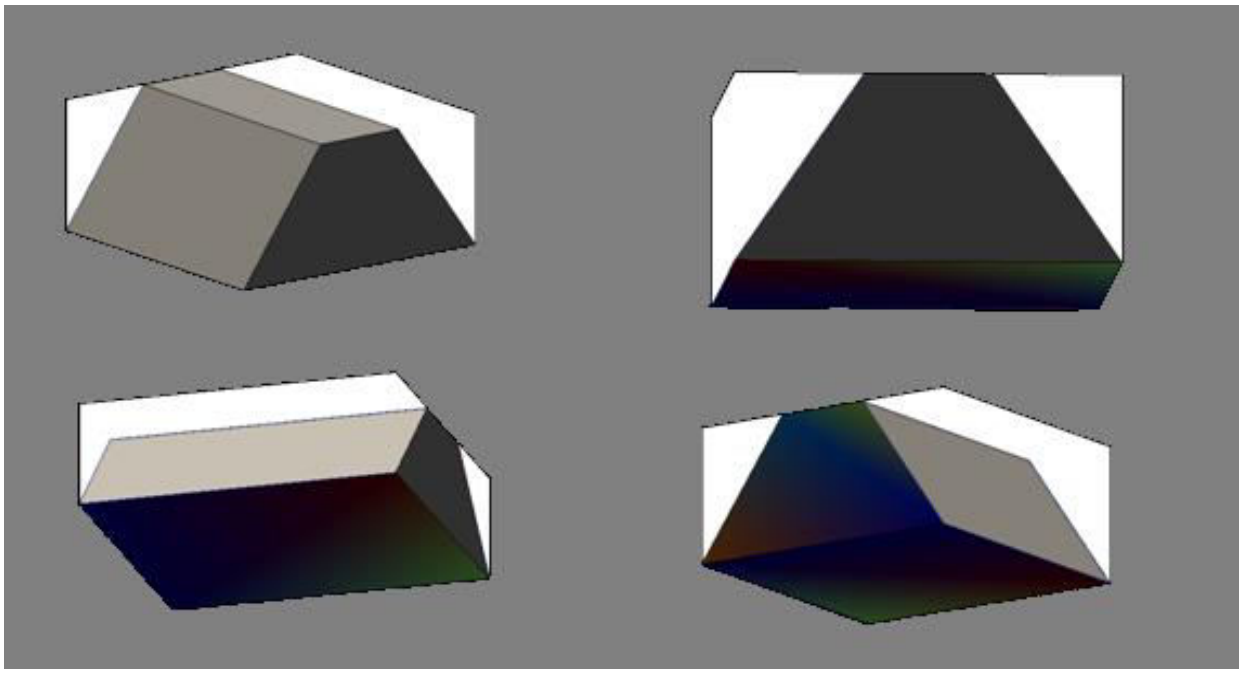


Figure No.5.2.3.1Spontaneous combustion mechanism in stockpile

The external air gets easily entrained in the edge of the stockpile due to abundant supply of oxygen is possible there. In case of center, air flow is impeded by coal particles and the amount of Oxygen is not enough to maintain chemical reaction of coal near the center. Accordingly, hot spot is initiated in the edge. Once hot spot is formed, heat is generated and the elevated temperature maintains hot-spot propagation. If heat generation is small or heat loss to the surroundings is excessive, hot spot is extinguished and ignition is not triggered.

Then, external air is entrained into the stockpile through the surface and the air entrainment is the most vigorous in the edge of the stockpile. Chemical reaction or oxidation of coal is maintained by the supply of oxygen in the air. Air inflow in the edge and abundant coal near the center move hot spot to the center. Heat is released from the coal by chemical reaction. One part of heat released is transferred to the surroundings and the other is accumulated inside the stockpile. As the hot spot moves to the center, its size and temperature increases continuously. Finally, it leads to spontaneous ignition.

5.2.4 Preventive Measures to suppress spontaneous ignition in coal stockpiles

There are several well-known methods to suppress spontaneous ignition of coal stockpiles. Some of them that are still under practiced are:-

I. Periodic compaction of stockpiles.
II. A low slope angle of the pile.
III. Pile protection by wind barriers.
IV. Water spray on the pile.
V. Covering the pile with an inert layer.

All the methods prevent coal from being reacted with oxygen in air and thereby, spontaneous ignition of coal stockpiles can be delayed by several days. But, the methods are less effective in suppression of ignition. So, new and fundamental methods are required to suppress spontaneous ignition of coal stockpiles more effectively. Based on the ignition process and mechanism, several suppression ideas or techniques are been proposed and verified. The chemical reaction rate with Arrhenius form, coal porosity, forced and natural convective flow both within coal stockpiles and in surrounding air are adopted to consider the physical and

chemical processes essential in simulating coal ignition. Two or three dimensional unsteady analyses are employed to predict ignition delay. Eliminating moisture content in coal and solar radiation a reasonable data can be obtained by numerical simulation without losing essential features in coal ignition.

A trapezoidal coal stockpile has been modelled as a porous medium to study the fluid flow, heat transfer, variation of maximum temperature, and heat removal phenomena under steady state condition.

Geometric Model of Coal stock piles and numerical procedure

The reactive flow field in a coal stockpile can be simulated by solving continuity, momentum, energy, and species equations simultaneously. The stockpile is considered to be a porous packing of coal particles with a mean diameter D_p, for simplification.

Fluid flow in porous media can be described by Darcy's law. The unsteady three-dimensional governing equations can be summarized using tensor notation as follows.

Continuity Equation,

$$\frac{\partial \alpha\rho}{\partial t} + \frac{\partial \alpha\rho v_i}{\partial x_i} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Momentum equation,

$$\frac{\partial \alpha\rho v_j}{\partial t} + \frac{\partial \alpha\rho v_j v_i}{\partial x_i} = -\alpha\frac{\partial p}{\partial x_j} + \alpha\beta_j - \frac{\alpha^2\mu}{k}\, v_j - \frac{\alpha^2\mu}{k} v_j - \frac{\alpha^3 C_F \rho}{\sqrt{k}}\sqrt{v_i v_j}\, v_j \ldots 2$$

Where $k = \frac{{D_P}^2\alpha^3}{150(1-\alpha)^2} \ldots\ldots\ldots\ldots\ldots 3$

Energy Equation

$$\frac{\partial \alpha \rho h}{\partial t} + \frac{\partial \alpha \rho_i v h}{\partial x_i} = \frac{\partial q_i}{\partial x_i} + \tau_{ji} \frac{\partial \alpha v_j}{\partial x_i} + \alpha \frac{\partial p}{\partial t} \ldots\ldots\ldots 4$$

Where q_i is the heat flux due to Thermal conduction radiation. It can be represented as

$$q_i = \lambda \frac{\partial T}{\partial x_i} + q_r + \sum_{k=1}^{Ng} j_{ki} h_k \ldots\ldots\ldots\ldots 5$$

Where λ is the thermal conductivity of the porous medium and can be written as

$$\lambda = -2\lambda_S + \frac{1}{\frac{\alpha}{2\lambda_{S_+} + \lambda_f} + \frac{1-\alpha}{3\lambda_S}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

Here λ_S and λ_f represents the thermal conductivities of the solid (coal) and fluid (pore) regions, respectively. The effective macroscopic thermal conductivity is based on the model of a medium where spherical gas volumes are surrounded by solid shells and has been verified for applications to porous media.

Species Equation

$$\frac{\partial \alpha \rho Y_k}{\partial t} + \frac{\partial \alpha \rho v_i Y_k}{\partial x_i} = \frac{\partial J_{ki}}{\partial x_i} + \omega_k \ldots\ldots\ldots\ldots\ldots 7$$

Where species diffusion flux is written as

$$J_{ki} = \rho D_{k,eff} \frac{\partial Y_k}{\partial x_i} + \frac{\rho D_{k,eff}^T}{T} \frac{\partial T}{\partial x_i} + \frac{\rho Y_k D_{k,eff}}{M} \frac{\partial M}{\partial x_i} - M \sum_l D_{k,eff} \frac{\partial Y_l}{\partial x_i} - \frac{\partial M}{\partial x_i} \sum_{l,eff} Y_l$$

$$- \rho Y_k \sum_l \frac{D_{l,eff}}{T} \frac{\partial T}{\partial x_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

The effective diffusion coefficients, $D_{k,eff}$ and $D_{k,eff}^T$ through porous media can be expressed as

$$D_{k,eff}^{(T)} = \alpha^{\gamma} D_k^{(T)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 9$$

Finally the equation of thermodynamic state can be expressed as

$$\frac{P}{\rho} = \left(\frac{R}{M}\right) T \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 10$$

The above equations, from (1)–(10) can be solved simultaneously with the help of appropriate numerical schemes and all simulations. When external flow is considered outside the stockpile, standard k-ε turbulent model is to be considered. The governing equations are discretized in space by finite difference scheme and the discretized equations can be solved with appropriate boundary conditions for two dimensional domain. For spatial discretization of the partial differential equations, 2nd-order upwind scheme can be taken into consideration and Crank Nicolson method can be used for time integration. Thus, the second-order accuracies are taken in respect to both space and time.

The dominant source of coal heating is coal oxidation on the surface of coal. Accordingly, surface reaction of coal is considered, but gas-phase reactions subsequent to the surface reaction are not. Moisture content and volatiles in coal are neglected because they don't have significant influence on coal heating. It is known that moisture content is a secondary factor of self-heating because heat of wetting is released through the processes of water adsorption and desorption. In another aspect, this can be more suitable for high-rank coals with little moisture content. The surface reaction of coal can be described by one-step chemical reaction:

$$C + O_2 \rightarrow \quad CO_2$$

Table No. 5.2.4.1Nomenclature and subscripts used in Equation

Nomenclature	
A = Pre-exponential factor ($kg \cdot s^{-1} kmol^{-0.7} m^{-0.9}$)	q = Heat flux ($J \cdot m^{-2} \cdot s^{-1}$)
B = Body force vector ($N \cdot m^{-3}$)	κ = Permeability (m^2)
C_F = Quadratic drag factor	λ = Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
D_k = Mass-diffusion coefficient of the k-th species ($kg \cdot m^{-2} \cdot s^{-1}$)	ρ = Fluid density ($kg \cdot m^{-3}$)
$D_{k,eff}$ = Effective mass-diffusion coefficient of the k-th species in a coal stockpile ($kg \cdot m^{-2} \cdot s^{-1}$)	μ = Fluid viscosity ($kg \cdot m^{-1}\ s^{-1}$)
$D^T_{k,eff}$ = Effective Soret diffusion coefficient of the k-th species in a coal stockpile ($kg \cdot m^{-2} \cdot s^{-1}$)	q_r = Radiative heat flux ($J \cdot m^{-2} \cdot s^{-1}$)
D_p = Mean diameter of a coal particle (m)	R = Universal gas constant ($J \cdot kmol^{-1} \cdot K^{-1}$)
E = Activation energy ($J \cdot kmol^{-1}$)	T = Temperature (K)
h = Enthalpy ($J \cdot kmol^{-1}$)	t = Time (s)
h_{iw} = Height of an internal wall (m)	v = Velocity ($m \cdot s^{-1}$)
h_k = Enthalpy of the k-th species ($J \cdot kmol^{-1}$)	x_i = i-th spatial coordinate (m)
h_{st} = Height of a coal stockpile (m)	Y_k = Mass fraction of the k-th species
J_k = Diffusion flux of the k-th species ($kg \cdot m^{-2} \cdot s^{-1}$)	α = Porosity of a coal stockpile
k = Reaction-rate constant (s^{-1})	γ = Tortuosity of a porous media
M = Mixture molecular weight ($kg \cdot kmol^{-1}$)	τ_{ij} = Viscous stress tensor ($N \cdot m^{-2}$)
N_g = the total number of gas-phase species	ω_k = Production rate of the k-th species ($kg \cdot m^{-3}\ s^{-1}$)
n = Temperature exponent	p = Pressure ($N \cdot m^{-2}$)
Subscripts	
F = Fluid	S = Solid
i = i-th component or summation index	j = j-th component or summation index
k= k-th species index	

The reaction-rate constant, k is expressed in the following Arrhenius form:

$$k = AT^{n}e^{-E/RT}$$

Where A as pre-exponential factor, E as activation energy and has the values of $2.1*10^{-10}$kg/(s·kmol$^{0.7}$·m$^{0.9}$) and 0.75 J/kmol respectively. Another combination of the chemical parameters adopted by Fierro et al. can be taken into consideration.

For numerical simulation of coal ignition, there are several combinations of the chemical parameters. But, any one combination of chemical parameters can be selected on the focused study for estimation of relative ignition delay in pursuit of new suppression methods. The temperature exponent for coal oxidation, n is needed to be so adjusted that the spontaneous ignition time predicted by the numerical analysis will agree well with the experimental data. Thermodynamic properties of the coal that can be taken in numerical study are

Physico-chemical properties and parameters of coal to be adopted for numerical simulation

Density of coal (kg/m^3)	1200	Prandtl number for air in surrounding atmosphere	0.707
Conductivity of coal(W/m·K)	0.12	Prandtl number for air in a coal stockpile	0.09
Specific heat of coal (J/kg·K)	1050	Schmidt number for air in surrounding atmosphere	0.7
Activation energy (J/kmol)	0.75	Schmidt number for air in a coal stockpile	3.8

The environmental situation cannot be considered completely in the numerical simulation as the measurable parameters are limited in the experiment. Accordingly, the most essential parameter, the ignition time is selected and adjustable parameter of temperature exponent is tuned to match the ignition time predicted numerically. Accordingly to experiments with the stockpile, it is known that spontaneous ignition is observed when 3 months have passed since the coal stockpile was made in a yard. Success or failure of spontaneous ignition is decided by whether the maximum temperature reaches 180 °C or not and it is possible to measure it. It is seen that the maximum temperature exceeds the critical temperature of 180 °C at a certain time within 3 months. In this numerical work, only the temperature exponent is adjusted for tuning of the numerical prediction to the measured stockpile. This adjustment can give us a good agreement although lots of physical processes are not considered.

5.2.5 Suggestive Measures

Slope of the stockpile:

A greater amount of slope obstructs the wind passage and so a large amount of air gets entered into the stockpile which enhances the oxidation of coal. The chance of air to be blown over the stockpile increases more for low slope angle. Hence the stockpile should be so designed such that there should be minimum hindrance to the air in flow. Generally a slope of (40º-45º) is preferred so that air may flow over the stockpile.

Shape of the Stockpile

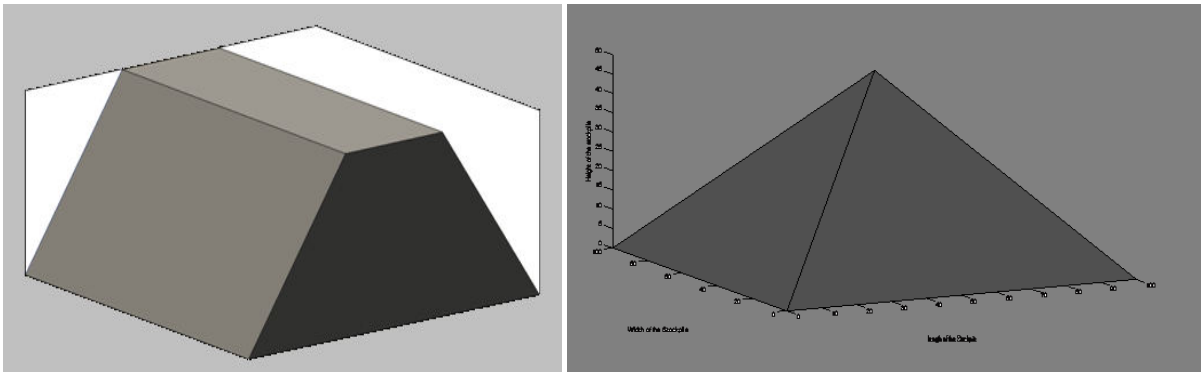


Figure No. 5.2.5.1 Shape of the Stockpile

Coal stockpile can be stacked in different shape. They are cone, prism, cut cone etc. The shape of the stockpile can provide us the criteria how heat is transferred from the surface to inside. The generation of hot spot and its location will be different for different types of stockpile. The hot spot is always formed just below the surface in the edge of the stockpile and it propagates towards the center. Hence, Shape of the stockpile can acts as an important criteria for the reducing susceptibility of coal.

Two closed faces

The larger the surface area exposed to air more will be the supply of oxygen. The more the supply of oxygen more will be the rate of oxidation. So the availability of smaller surface area will reduce the amount of oxygen which can be helpful in increasing the incubation period of the stockpile. In case of trapezoidal stockpile if two phase of the stockpile are kept closed than oxygen availability will be from

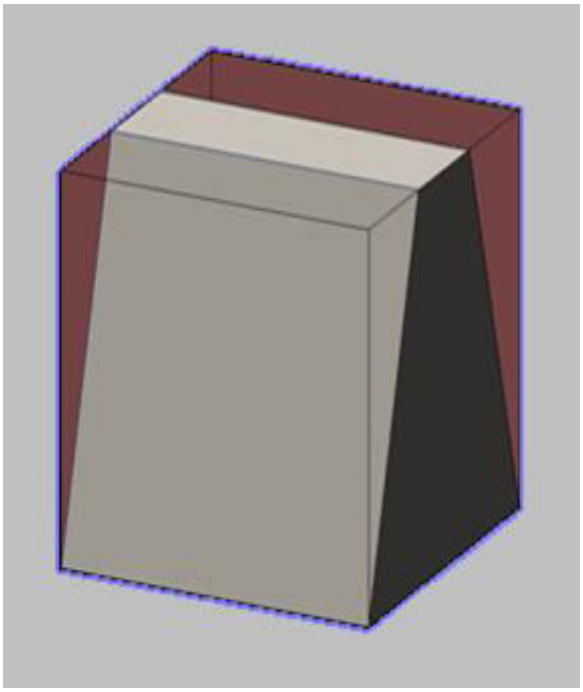


Figure No. 5.2.5.2 Two Faced Closed of a stockpile

other two phase only. Hence oxygen availability will be less and it can consider a method to reduce oxidation of coal

Use of Protective Covering

Inert covering material such as tarpaulin sheets with sufficient heat resistivity can be used to cover the openly kept stockpile to reduce the loss of calorific value and further oxidation of coal. It helps in cutting off oxygen to come in contact with coal. The control and prevention of spontaneous combustion focus on removing oxygen or preventing its access to the fuel. This is usually best accomplished by the applying cover layers of inert material which reduce the rate at which oxygen can penetrate the spoil pile. The best cover materials are clays which can retain residual moisture. Moisture is important because it acts to seal off oxygen pathways, thus preventing the oxidation reaction from proceeding. Inert covering material such as tarpaulin sheets with sufficient heat resistivity can be used to cover the openly kept stockpile to reduce the loss of calorific value and further oxidation of coal. It helps incutting off oxygen to come in contact with coal.

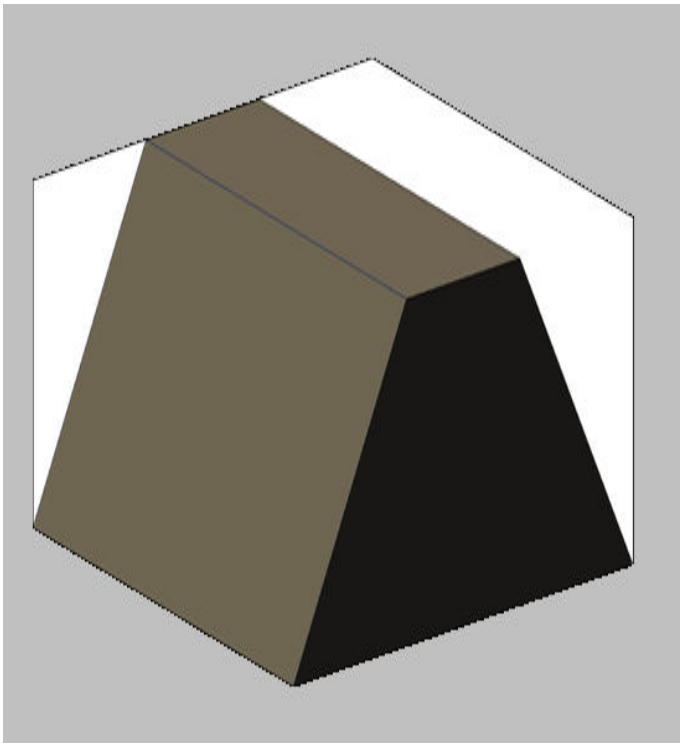


Figure No. 5.2.5.3 Use of Protective Covering in Stockpile

Dimension of Coal pile

Size and area of stockpile should be based not only on estimated tonnage but also on design principles of stockpile management. Proper dimensioning of stockpiles helps negate weathering of coal. Just dumping the coal in a big pile might lead to problems. Rather coal should be packed in horizontal layers of about 1.3 to 3 feet high followed by leveling and compaction by dozers. It helps in evenly distribution of coal thus avoiding segregation of fine coal. Pile unlayered, uncompacted high grade coal should be limited to about 15 feet and while layered and packed coal pile height should be limited to about 26 feet.

Particle size

If the stockpile is of mainly medium to fine particle then making it finer or adding fines will help in delay of spontaneous combustion. If the pile consists of coarse particles of relatively low reactivity then removing the finer material will also act as the inhibitor for coal oxidation.

5.2.6 Conclusion

Although the methods are not optimized, it is predicted that spontaneous ignition can be retarded appreciably up to 50 days or so by these new methods. The importance is given more for the possibility and effectiveness with respect to ignition delay. The suppression capability of each method can be improved by design optimization of the hardware adopted in each method. These actions can and will help in saving coal. For their practical applications to the field, several parameters can be taken into account.

5.3 Protective measures during Mining

5.3.1 Introduction

Application of inhibiting agents is one of the possible ways of preventing spontaneous combustion of coal. The basic principle of action is hindering the access of oxygen to the coal surface when coated by the additive solution. The ability of the additives to inhibit the oxidation process differs differently for different chemicals. However, these interactions are observed at temperatures exceeding 300 °C due to unsaturated carbon chain reactions.

5.3.2 Theory

Two basic theories may be used to help in the selection of agents for suppressing the self-heating of coa1.

1. The oxygen adsorption on the coal surface during the initiation period produces functional groups or initiates radical reactions. Therefore, inhibitors are chosen to reduce the formation of functional groups or stop the radical reactions. These would be mainly organic compounds, but they are generally toxic and corrosive.

2. There are active centres on the surface of coal at which the oxidation reaction occurs. Thus, agents may be selected to cover the active centres on the coal surface. Some known organic covering agents improve the inhibiting effect, but their effectiveness is limited and they cause environmental pollution.

Water as a retardant

The single effect of water in extinguishing application is its high cooling capacity. There are several well known situations, however, in which application of water actually serves

to intensify the fire. When water is applied onto very hot coal fire, water flashes into steam with possible spattering effects that can spread the area of fire. Flashing of water on red-hot coal fire debris can produces water gas, containing carbon monoxide and hydrogen gas, which are poisonous and highly explosive in nature, respectively. Hence there is a need for alternative for reducing the effect of spontaneous combustion.

5.3.3 Selection of Retardants

The application of fire retardant is dependent on many factors and the most important amongst them is that the retardant

1. It should not be toxic in nature.
2. It must not generate noxious gases during its production and application in mines.
3. The solubility in water should be high.
4. Easy application in the actual condition
5. Economical viability along with ease of availability.
6. It is desired that it should not harm the personnel who are involved during application.
7. The retardant should be in the capacity of increasing the cooling capacity of water, produce endothermic characteristics and reduce the occurrence of water gas explosion in case of used on high temperature coal fire.

Table No. 5.3.3.1 Result of Flammability Temperature of Coal with Sodium Nitrate

Sl. No.	Sample Code	Flammability Temperature(˚C)	With Sodium Nitrate($NaNO_3$)				
			5%	10%	15%	20%	25%
1	MCL1	505	620	625	625	620	620
2	NEC	495	510	515	515	515	510
3	SECL1	540	655	655	660	660	655
4	WCL	515	630	635	635	635	630
5	SCCL	415	530	535	530	530	525
6	BCCL	455	570	575	575	570	570
7	SECL2	545	660	665	665	660	660
8	MCL2	530	650	650	655	655	650
9	MCL3	500	615	620	620	615	615
10	MCL4	560	675	680	680	675	675

On adding Sodium Nitrate to coal, the flammability temperature rises by nearly 115˚C. For 5% of sodium nitrate there is a rise by115, for 10% it is 120 and for 15% it is 125˚C.But on further increasing the percentage of sodium nitrate the flammability point remains constant and decreases further. So there is a rise of 125˚C if coal composition contains15% of sodium nitrate.

Table No. 5.3.3.2 Result of Flammability Temperature of Coal with Fused Calcium Chloride

Sl. No.	Sample Code	Flammability Temperature(˚C)	With Fused Calcium Chloride($CaCl_2$)				
			5%	10%	15%	20%	25%
1	MCL1	505	540	540	545	545	560
2	NEC	495	510	515	515	520	530
3	SECL1	540	575	575	580	580	595
4	WCL	515	550	550	555	555	570
5	SCCL	415	445	450	450	450	470
6	BCCL	455	490	490	495	495	510
7	SECL2	545	580	585	585	585	600
8	MCL2	530	565	565	570	570	580
9	MCL3	500	535	535	540	540	555
10	MCL4	560	595	600	600	600	615

It is observed that if coal composition contains 5%calcium chloride the flammability temperature increases by 35˚C and on increasing it to 10% it increases to 40˚C.But on further increasing it remains nearly constant. So, we can conclude that if coal contains 10% of calcium chloride than the flammability temperature is increased by 40˚C.

Table No. 5.3.3.3Result of Flammability Temperature of Coal with Sodium Chloride

Sl.No.	Sample Code	Flammability Temperature(˚C)	With Sodium Chloride				
			5%	10%	15%	20%	25%
1	MCL1	505	550	555	555	550	550
2	NEC	495	535	540	540	540	535
3	SECL1	540	585	590	590	595	590
4	WCL	515	560	560	560	565	560
5	SCCL	415	465	465	470	470	470
6	BCCL	455	500	505	505	505	500
7	SECL2	545	590	590	595	595	590
8	MCL2	530	575	580	580	585	580
9	MCL3	500	550	545	550	550	555
10	MCL4	560	600	610	615	615	615

Considering sodium chloride as an additive it is seen that the flammability temperature of coal is increased to 50˚C. If the composition contains 5% of sodium chloride its flammability rises by 45˚C and if it is increased to 10% than there is a rise by 50˚C.But if the composition contains 25% or more of sodium chloride than the rise of flammability temperature remains the same. It remains constant for 15%, 20% and slightly increasing for 25%.

The highest rise of temperature is seen by adding sodium dodecyl sulphate. If the composition contains 15% of sodium dodecyl sulphate the flammability temperature is increases by 125˚C. It remains same for 15 % and 20%. Further rise in percentage of additive decreases the flammability temperature.

Table No. 5.3.3.4 Result of Flammability Temperature of Coal with Sodium dodecyl sulphate

Sl. No.	**Sample Code**	**Flammability Temperature (˚C)**	**With Sodium dodecyl sulphate**				
			5%	10%	15%	20%	25%
1	MCL1	505	625	625	630	625	625
2	NEC	495	605	610	615	615	610
3	SECL1	540	655	660	660	660	660
4	WCL	515	635	635	630	630	625
5	SCCL	415	530	535	530	530	525
6	BCCL	455	570	575	575	575	570
7	SECL2	545	660	660	665	660	660
8	MCL2	530	645	650	650	650	650
9	MCL3	500	615	620	615	615	615
10	MCL4	560	670	670	675	675	675

5.3.4 Conclusion

The mechanism of inhibition is still unclear. But it appears that a combination of thermal, chemical, and physical phenomena contribute to the process. No single parameter accounts for the behaviour of the additives. The relative order of effectiveness was

Calcium Chloride >Sodium Chloride> Sodium Nitrate> Sodium dodecyl sulphate

These are safer in the practical application as an inhibiting agent for coals and also convenient for storage, transportation, and treatment and mining. These non-toxic combinations neither generate any noxious gases nor inflict any harm to the personals during application in the actual field. Optimization of suitable combination of mixture will be helpful in making the use of retardants in terms of cost and working efficiency. There may be more number of chemicals or different permutation and combination of chemicals which are required to be studied to determine the suitability of fire retardant for prevention and control of fires.

Chapter 6

DISCUSSION & CONCLUSION

Discussion

Conclusion

6.1Discussion

1. The moisture content of the various coal samples varied from 1.3% to 13.575% with MCL1 being the highly moist coal and BCCL1, the least moisture content. High moisture content in MCL1 is because the seam is watery in nature which justifies field observation.

2. High moisture content and low fixed carbon in SECL1 conveys the coal seam is highly prone to spontaneous heating.

3. Low fixed carbon content along with high volatile matter content in SCCL1 shows the coal seam is highly susceptible to spontaneous heating.

4. Low moisture content and high fixed carbon content in BCCL1 & NECL1 conveys these seam do not pose any spontaneous heating problem. In fact they are poorly susceptible to spontaneous heating.

5. The average values of moisture, relatively high value of volatile matter in case of MCL2, SECL2, WCL, MCL1, shows they are moderately to poorly susceptible to spontaneous heating.

6. High Gross Calorific Value of the samples NECL1, BCCL1 shows that they are good rank coal and hence very less susceptible to spontaneous heating.

7. The highest Wet Oxidation Potential Difference in case of MCL3 shows that it is highly prone to rapid oxidation resulting in highly susceptible to spontaneous heating problems.

8. Averagely high value of Wet Oxidation Potential Difference in case of MCL1, MCL2 and WCL1 suggests these respective coal seams are moderately susceptible to spontaneous heating.

9. Low values of Wet Oxidation Potential Difference in case of BCCL1, NECL1 claims that these seams are less susceptible to spontaneous heating.

10. Lowest Flammability temperature of SCCL1 shows that it is highly prone to spontaneous heating.

11. High Crossing Point Temperature of BCCL1 & NECL1 shows that they are poorly susceptible to spontaneous heating.

12. SCCL1 has the lowest Crossing point temperature value which claims that it is highly susceptible to spontaneous heating and field investigation also supports the argument.

13. Relatively average values of Crossing point temperature of samples from MCL1, WCL1, SECL2 and MCL2 shows that they are moderately susceptible to spontaneous heating.

Above discussion shows that most of the Indian coals are moderately to poorly susceptible to spontaneous heating where as few seams are totally free of spontaneous heating related issues.

Correlation studies were carried out between various susceptibility indices and the coal properties as obtained from proximate analysis. The susceptibility parameters were taken as dependent variables where as the coal properties were taken as independent variables and the correlation coefficients were found out. Also the trendline curves were modelled to show the dependence of susceptibility indices on the various coal intrinsic properties.

Table No.6.1.1Correlation coefficients between various susceptibility parameters and the proximate analysis values.

Sl No.	Dependent variable	Independent variable	Correlation coefficient(r)
1.	CPT	Moisture	-0.56688
2.	CPT	Volatile matter	-0.13148
3.	CPT	Ash Content	-0.16588
4.	Flammability temperature	Moisture	0.287654883
5.	Flammability temperature	Volatile Matter	0.290374585
6.	Flammability temperature	Ash Content	-0.012064644
7.	Wet Oxidation Potential Difference	Moisture	0.566427615
8.	Wet Oxidation Potential Difference	Volatile Matter	0.0874
9.	Wet Oxidation Potential Difference	Ash Content	0.319305702
10.	WITS-EHAC	Moisture	0.66

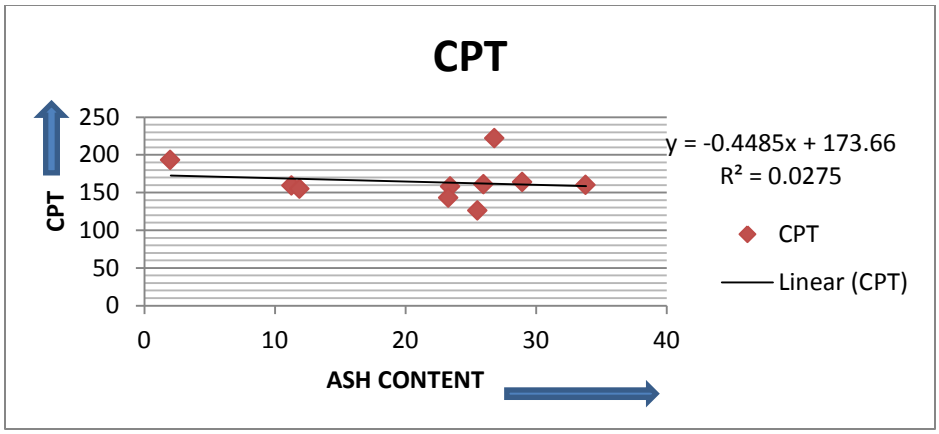


Fig no 6.1.1 variation of CPT vs Ash Content

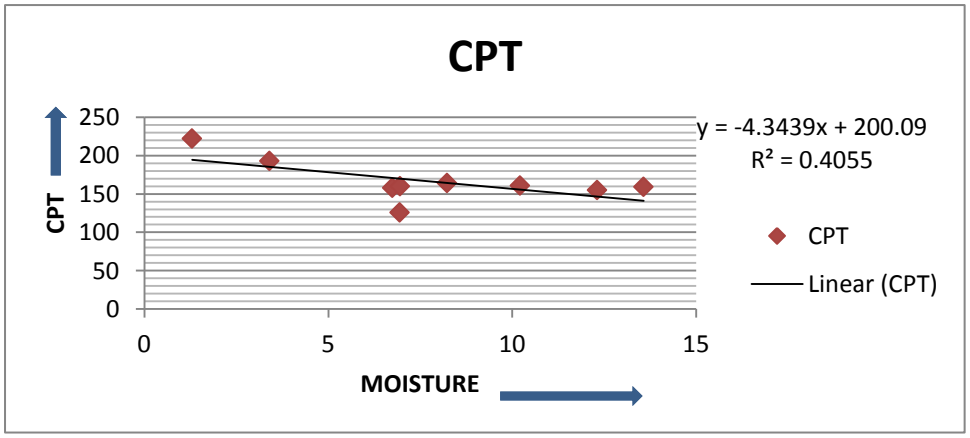


Fig no 6.1.2 variation of CPT vs Moisture

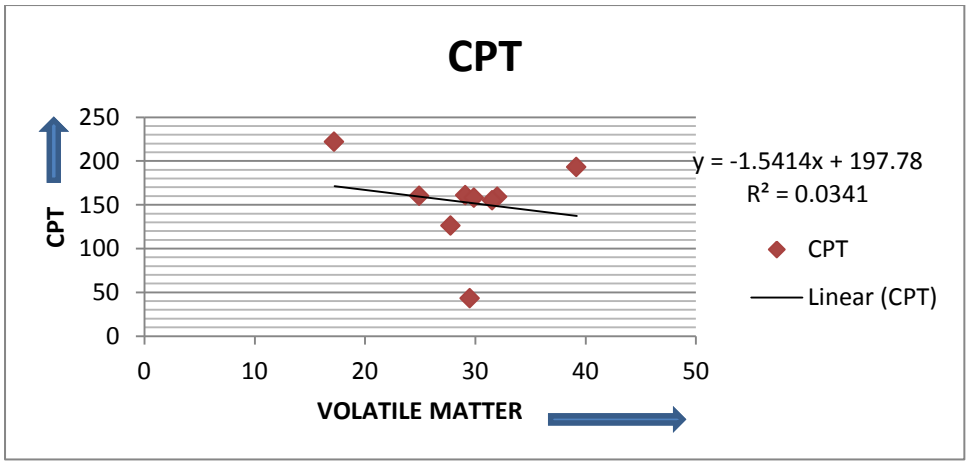


Fig no 6.1.3 Variation of CPT vs Volatile Matter

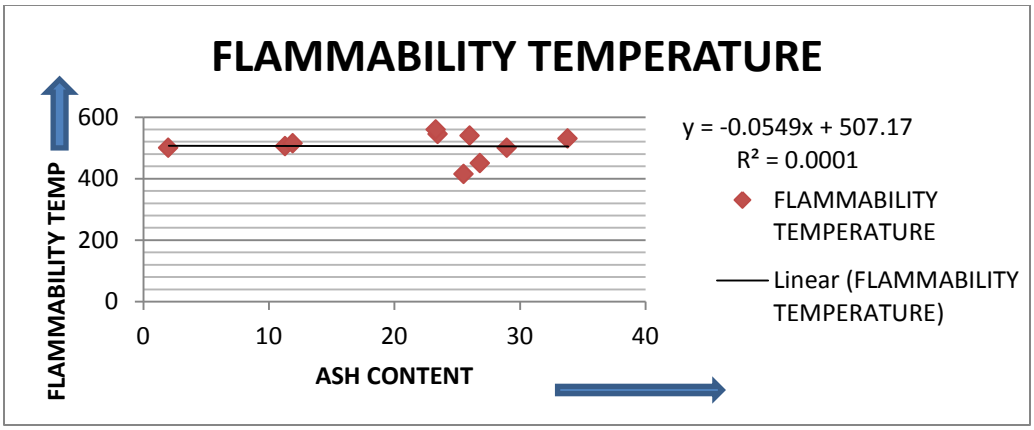


Fig no 6.1.4 Variation of Flammability temperature vs Ash Content

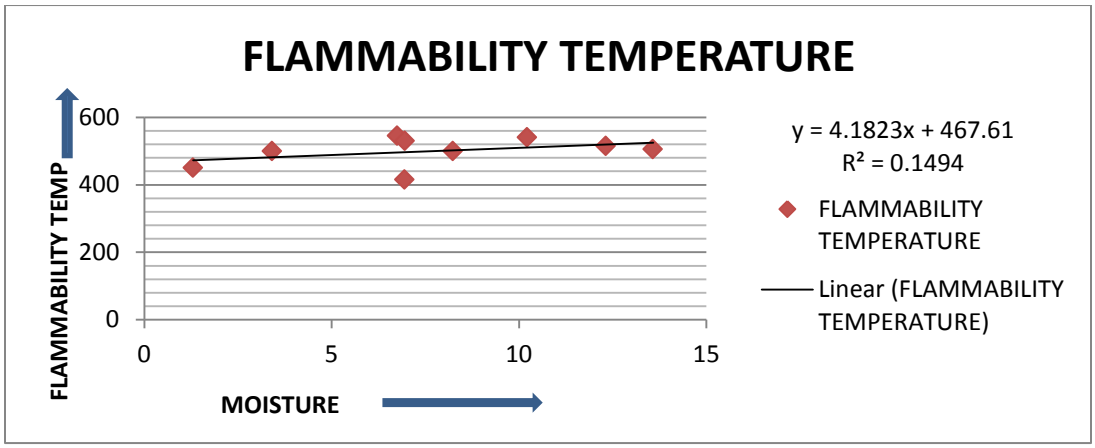


Fig no 6.1.5 Variation of Flammability temperature vs Moisture

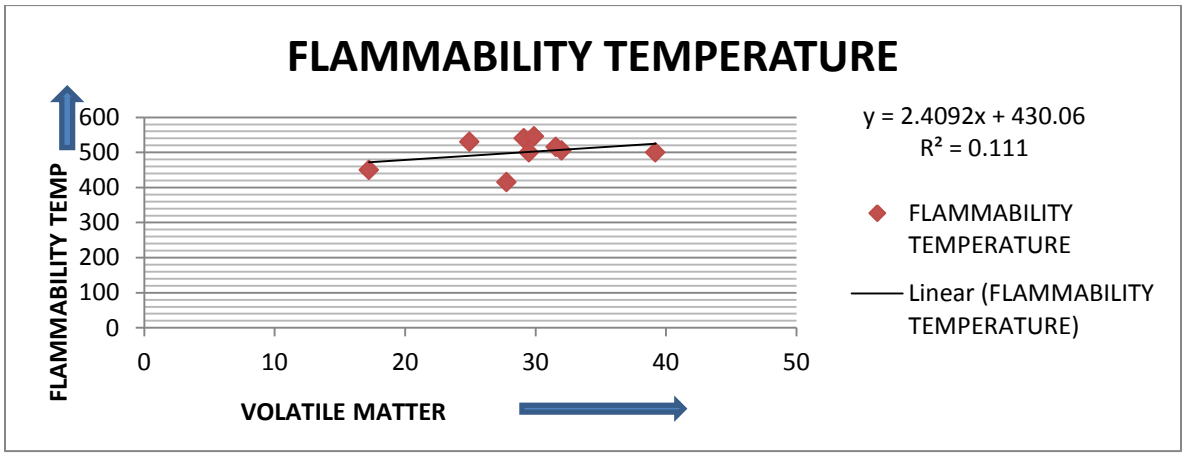


Fig no 6.1.6 Variation of Flammability vs Volatile Matter

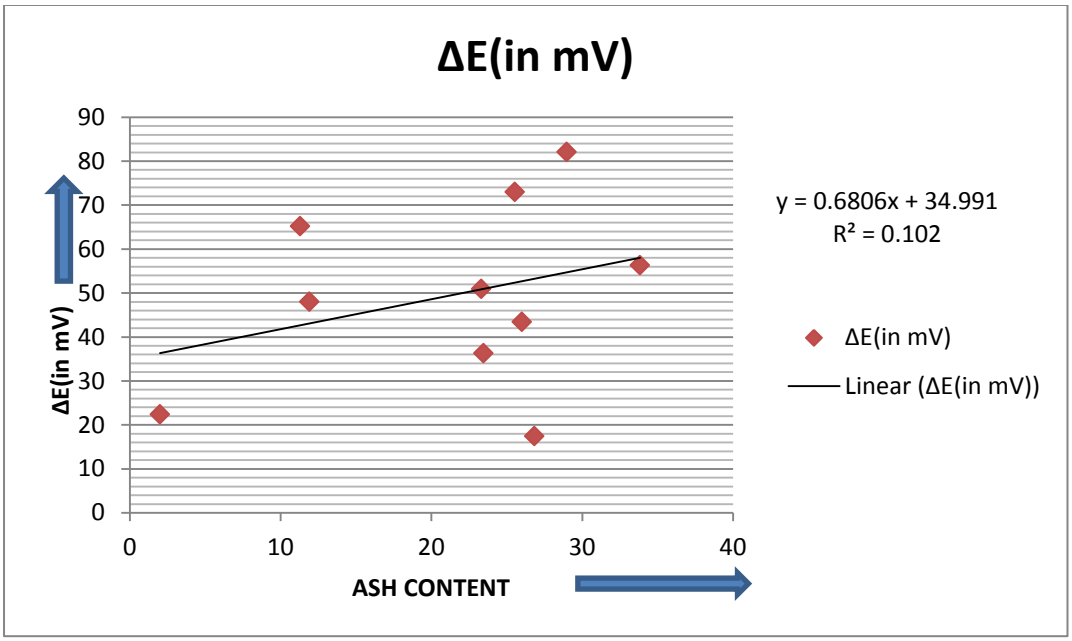


Fig no 6.1.7 Variation of ΔE vs Ash Content

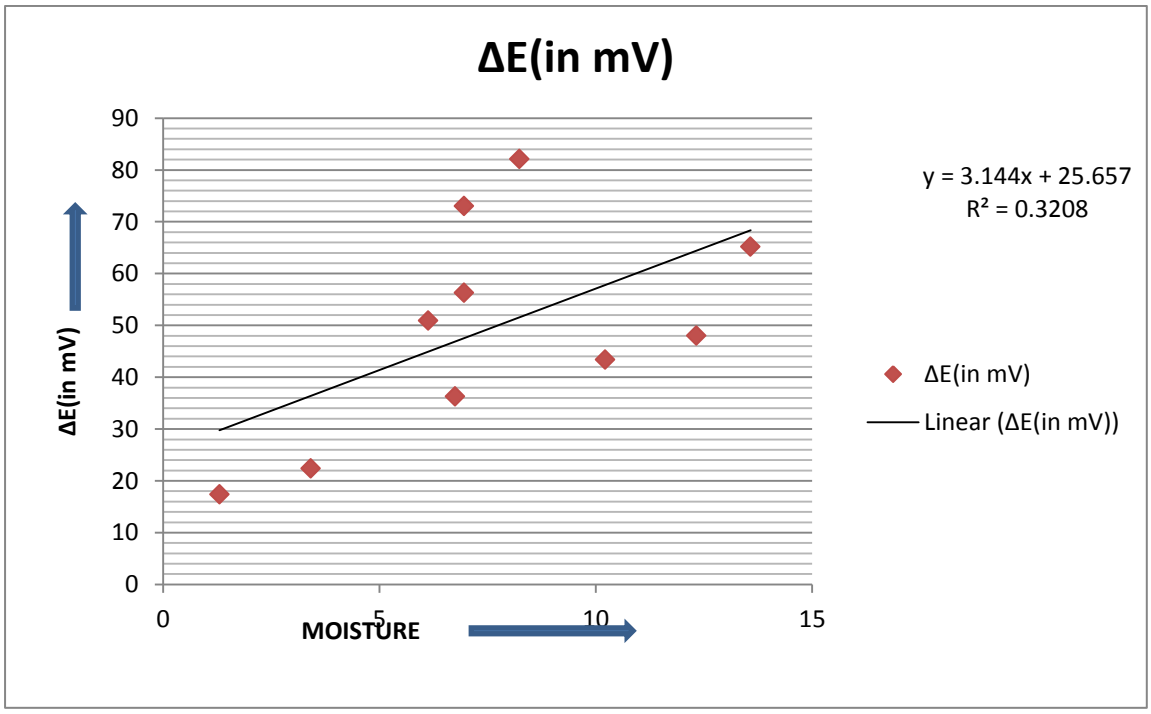


Fig no 6.1.8 Variation of ΔE vs Moisture

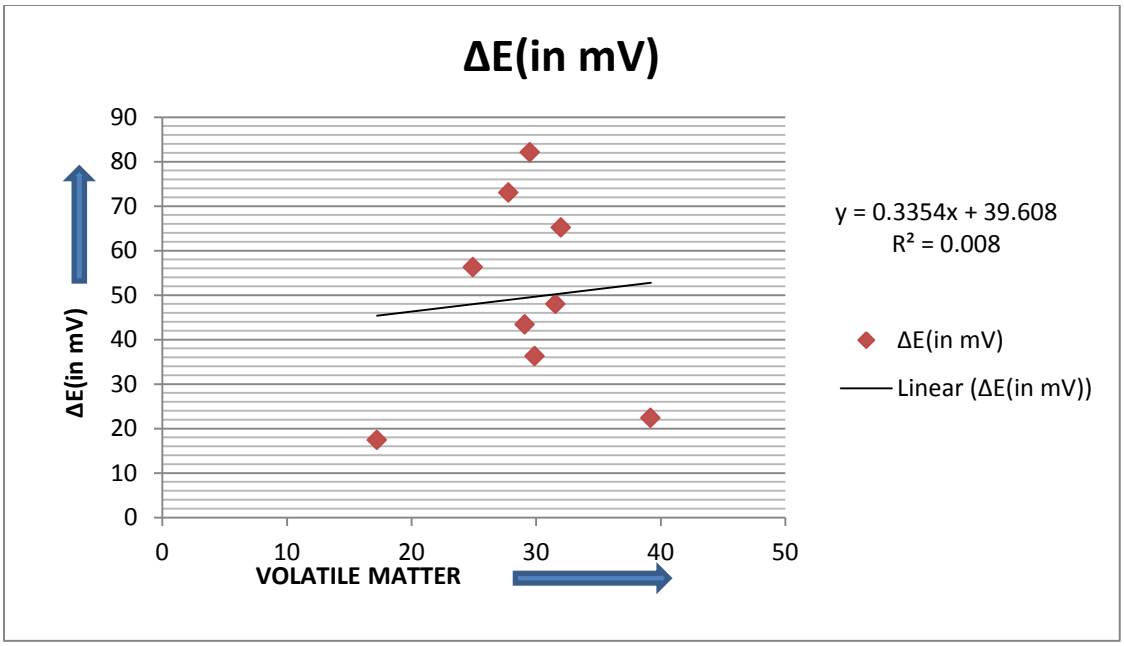


Fig no 6.1.9 Variation of ΔE vs Volatile Matter

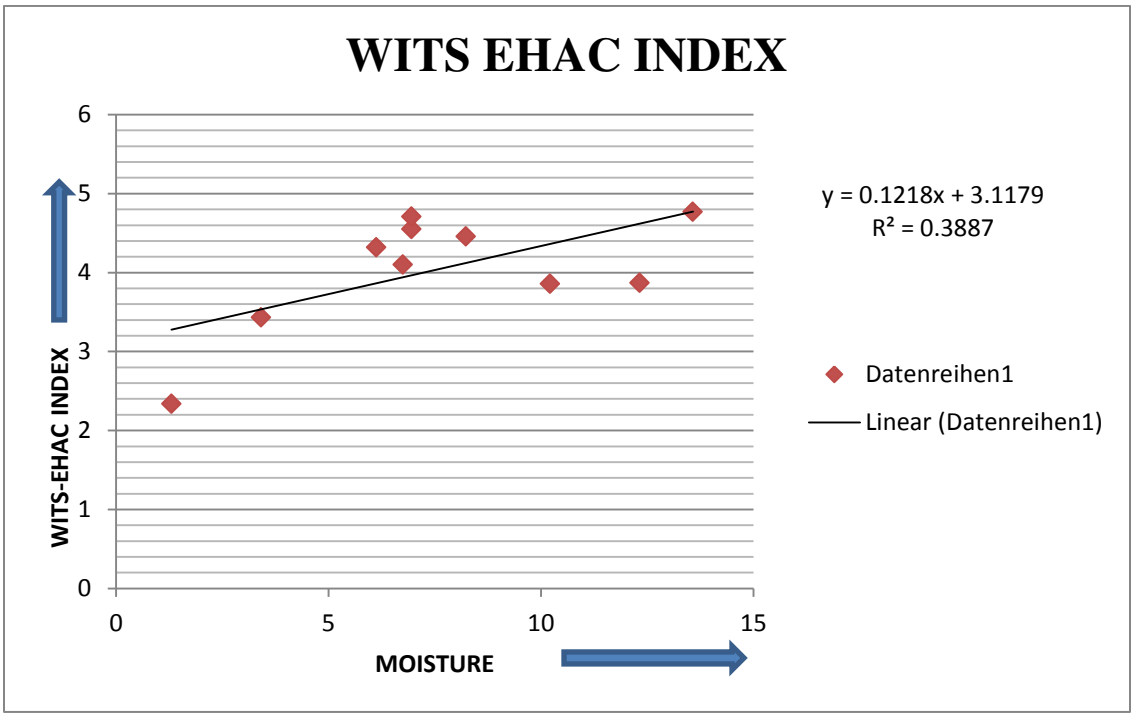


Fig no. 6.1.10 Variation of the WITS-EHAS vs. Moisture

6.3 Conclusion

1. The results shown by Crossing Point Temperature value and Wet Oxidation Potential Difference value regarding liability of the coal samples towards spontaneous heating were quite similar. Both the experimental results suggested SCCL1 sample as highly susceptible and BCCL1 as least susceptible.

2. Wet Oxidation Potential Method showed productive results in determining spontaneous heating liability of coal samples showing similar results as CPT. Thus it can be used as a handy experimental tool in predicting spontaneous heating susceptibility of both high and low moisture coals. In addition to that it takes just 30 minutes for completion of the entire experiment in comparison to 2 hrs used in case of Crossing Point Temperature.

3. Flammability temperature cannot be considered as a sound experimental technique for determining spontaneous heating liability of various coal samples as it showed poor correlation with all the coal properties.

4.Both Wet Oxidation Potential Difference and Crossing Point Temperature showed high correlation value with moisture content of coal justifying their use in determining spontaneous heating liability of coal samples.

5. Crossing Point Temperature is used as a handy experimental technique in prediction of spontaneous heating liability in India but many a times it fails in predicting the spontaneous heating liability of high moisture coals. Also it is a time consuming process and reproducibility of similar results is seldom.

6. Wet Oxidation Potential Difference is an effective tool for determining spontaneous heating tendency for all types of coals and it produces faster results but still no proper guideline has been mentioned till date in order to standardise the potential difference values with respect to liability of coal towards spontaneous heating.

On the basis spontaneous heating liability it can be concluded that Protective Measures for storage and mining of coal is a highly essential need. For storage purposes, it is generally done in stockpile. Hence few relevant techniques that can be applied are been suggested. Further quantitative analysis work has to be carried out for the safety purposes.

For coal waste or for low grade coal, suggested protective measures in the spoil pile can be taken into account. These do not quantify the cases but can prove economical and beneficial for the mine.

In case of mining, inhibitors are recently used for delaying the spontaneous combustion. Sodium dodecyl sulphate has the highest range but there may be possibility of emission of noxious gases. Intermixing of chemicals may serve the purpose of delaying the spontaneous combustion with a higher range of temperature.

Chapter 7

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7.1 References

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